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TESTS OF ROCK CORES, WARREN SITING AREA, WYOMING

Kenneth L. Saucier, et al

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

March 1969

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TESTS OF ROCK CORES WARREN SITING AREA, WYOMING

by

K. L. Saucier

D. L. Ainsworth

March 1969

Sponsored by

Space and Missile Systems Organization

U. S. Air Force Systems Command

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PERSON CALLED	OFFICE	PHONE NUMBER AND EXTENSION

OUTGOING CALL

PERSON CALLING	OFFICE	PHONE NUMBER AND EXTENSION
Mr. James M. Polatty	Concrete Division	

PERSON CALLED	ADDRESS	PHONE NUMBER AND EXTENSION
Captain B. W. Bullard	Space & Missile Systems Organization	

SUMMARY OF CONVERSATION

I called SAMSO and talked to CPT Bullard. CPT Bullard was familiar with the WES reports covering rock tests for SAMSO. I explained the requirements of AR 70-31. He agreed that Statement A should be utilized on all of the SAMSO rock test reports.

James M. Polatty

JAMES M. POLATTY, Chief
Engineering Mechanics Branch
Concrete Division

Copy furnished:
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Laura Hanisee said following MP's covering rock tests for SAMSO were to be changed to Statement A :

C-69-3
C-69-12
C-69-16
C-70-4
C-70-6
C-70-7
C-70-9
C-70-10
C-70-11
C-70-14
C-70-16
C-70-17

DA FORM 751, 1 APR 66 — REPLACES EDITION OF 1 FEB 58 WHICH WILL BE USED.

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ARMY-MRC VICKSBURG, MISS.

ABSTRACT

Laboratory tests were conducted on rock core samples received from ten core holes drilled in the Laramie range, Wyoming, to determine the integrity and mechanical behavior of the materials. The results were to be used to determine the usefulness of the Warren Siting Area for potential missile sites. Series I tests (relative hardness, specific gravity, compressive strength, sonic velocity, etc.) indicated the materials to be relatively uniform, competent granite, diorite, and gneiss rock. Series II tests (triaxial, hydrostatic, and confined compression) indicated the rock to be rather incompressible and brittle up to 36,000-psi triaxial stress. Series III tests indicated that the granite and diorite had Hugoniot elastic limits of 50 kilobars or more and the gneiss approximately 20 kilobars. In order to better define the physical and mechanical behavior of the rock, triaxial tests to approximately 150,000 psi on intact and jointed specimens and equation of state tests at pressures to approximately 600 kilobars should be conducted.

PREFACE

This study was conducted in the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the U. S. Air Force Space and Missile Systems Organization (SAMSO) of the Air Force Systems Command. The study was coordinated with 1LT Rupert G. Tart, Jr., SAMSO Project Officer, and Mr. Norman P. Langley of Aerospace Corporation, San Bernardino, California. The work was accomplished during the period June 1968 to February 1969 under the general supervision of Mr. Bryant Mather, Chief, Concrete Division, and under the direct supervision of Messrs. J. M. Polatty, Chief, Engineering Mechanics Branch, W. O. Tynes, Chief, Concrete and Rock Properties Section, and K. L. Saucier, Project Officer. Project leaders were Mr. D. L. Ainsworth for the special (Series III) tests, Mr. A. D. Buck for the petrography work, and Mr. E. E. McCoy for the thermal and sonic work. Mr. Saucier performed the majority of the program analysis, and prepared this report with the assistance of Mr. Ainsworth.

Directors of the WES during the investigation and the preparation and publication of this report were COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE. Technical Director was Mr. J. B. Tiffany; Assistant Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows.

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
feet per second	0.3048	meters per second
pounds	0.45359237	kilograms
pounds per square inch	0.070307	kilograms per square centimeter
kips per square inch	70.307	kilograms per square centimeter
pounds per cubic foot	16.0185	kilograms per cubic meter

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The purpose of this study was to supplement the information being obtained for the hard rock missile-siting investigation by the U. S. Air Force Space and Missile Systems Organization (SAMSO). It was necessary to define the properties required on the specific materials for utilization in the various computer codes for ground-motion predictions and as necessary for design of structures in the medium. Results of tests on cores from the Laramie range near Warren AFB, Wyoming, are reported herein.

1.2 OBJECTIVE

The objective of this investigation was to conduct laboratory tests on samples from potential missile sites to determine the integrity and the mechanical behavior of the materials as completely as possible, analyze the data thus obtained, and report the results to appropriate users.

1.3 SCOPE

Laboratory tests were conducted as indicated on the following page on samples received from the field. Table 1.1 gives pertinent information on the various tests.

Series I tests, conducted to determine the general quality, uniformity, and integrity of the rock in the area sampled: (1) relative hardness (Schmidt number), (2) specific gravity, (3) porosity, (4) indirect tension, (5) unconfined shear, (6) unconfined compression, (7) cyclic compression, (8) dynamic moduli, (9) sonic velocity, and (10) petrographic examination.

Series II tests, conducted to define the elastic properties of selected types of rock under various states of stress: (1) triaxial compression, (2) hydrostatic compression, and (3) confined compression.

Series III tests, conducted to define the pressure-volume relation of selected types of rock at very high rates of load: (1) low pressure (air gun) and (2) high pressure (explosives).

1.4 SAMPLES

Samples were received from 10 holes in the Warren Siting Area designated as Laramie and CR-4, -10, -15, -19, -32, -35, -39, -42, and -48. All samples were NX size cores (2-1/8-inch[1] diameter) except the Laramie core which was 1-7/8 inches in diameter. Test specimens of the required dimensions as given in Table 1.1 were

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[1] A table of factors for converting British units of measurement to metric units is presented on page 7.

prepared for the individual tests. Series I tests were conducted on selected specimens from all holes. Series II and III tests were conducted on specimens of the Laramie core and core from Holes CR-42 and CR-10.

1.5 REPORT REQUIREMENTS

The immediate need for the test results required that data reports be compiled and forwarded to the users as work was completed on each hole. The data reports of the individual test results are included herein as Appendixes A through L.

TABLE 1.1 SUMMARY OF TESTS

Test	Specimen Size	Test Equipment	Recording Equipment	Measured Properties	Computed Properties
Series I:					
Relative hardness	1 diam by 2 diam	Schmidt hammer	--	Relative hardness	--
Specific gravity		Scales	--	Specific gravity	Density
Porosity		Pressure pycnometer	Scales	Porosity, percent	--
Indirect tension		440,000-pound test machine	--	Tensile strength	--
Unconfined shear		Shear test apparatus	Testing machine	Shear strength	--
Unconfined compression		440,000-pound test machine	X-Y recorder	Compressive strength	--
Cyclic compression					Young's, shear, and bulk moduli and Poisson's ratio
Dynamic moduli	1 diam by 3 diam	Sonic driver, pickup, amplifiers	Oscilloscope display	Fundamental frequencies	
Sonic velocity		Ultrasonic transducers		Compressional velocity	Shear velocity
Petrographic examination	Variable	Microscopes, X-ray diffraction	--	Appearance, texture, and mineralogy	--
Series II:					
Triaxial compression	1 diam by 2 diam	Triaxial chamber, 440,000-pound test machine	X-Y recorder	Triaxial strength	Failure envelope
Hydrostatic compression				Deformability	Bulk modulus
Confined compression					Constrained modulus
Series III:					
Low pressure	1 diam by 1 inch	Air gun	Oscilloscopes	Particle velocity, shock velocity	Pressure, volume change
High pressure	1 diam by 1/2 inch	Explosives			

CHAPTER 2

TEST METHODS

2.1 SCHMIDT NUMBER

The Schmidt number is a measure of the relative degree of hardness as determined by the degree of rebound of a small mass propelled against a test surface. Twenty-four readings per specimen were taken as suggested by Deere and Miller.[1] The average of these readings is the Schmidt number or relative hardness. The hardness is often taken as an approximation of rock quality, and may be correlated with other physical tests such as strength, density, and modulus.

2.2 SPECIFIC GRAVITY AND POROSITY

The specific gravity of the "as-received" samples was determined by the loss of weight method conducted according to method CRD-C 107 of the "Handbook for Concrete and Cement."[2] A pycnometer is utilized

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[1] Deere, D. U. and Miller, R. P.; "Engineering Classification and Index Properties for Intact Rock"; Technical Report No. AFWL-TR-65-116, December 1966; Air Force Weapons Laboratory, Kirtland Air Force Base, N. Mex.; Unclassified.

[2] U. S. Army Engineer Waterways Experiment Station, CE; "Handbook for Concrete and Cement"; August 1949 (with quarterly supplements); Vicksburg, Miss.; Unclassified.

to determine the loss of weight of the sample upon submergence. The specific gravity is equal to the weight in air divided by the loss of weight in water.

Porosity, herein defined as the volume of voids expressed as a percentage of total volume, was determined after the samples utilized for the specific gravity test had been dried to constant weight. The amount of water forced into the test sample under 1200-psi fluid pressure in a pressure pycnometer was carefully measured. Utilizing the known density of the water, the void space in the test sample was calculated. For very dense material, the sample was broken into small pieces to allow the fluid to saturate it.

2.3 TENSILE AND SHEAR STRENGTHS

The tensile strength was determined by the indirect method, commonly referred to as the tensile splitting or Brazilian method, in which a tensile stress is induced in a cylindrical test specimen by a compressive force applied on two diametrically opposite line elements of the cylindrical surface. The test was conducted according to method CRD-C 77 of the "Handbook for Concrete and Cement".[2]

The shear strength was determined directly by the single-plane method described in CRD-C 90.[2] The method consists essentially of forcing a shear plane by holding one end of a test specimen

stationary and moving the other end perpendicular to the axis of the specimen.

2.4 DYNAMIC PROPERTIES

Bulk, shear, and Young's moduli, Poisson's ratio, and shear velocity were determined on selected rock samples by use of the method of vibrating unconfined samples in the fundamental modes of vibration. The resonant frequencies were utilized to compute the aforementioned elastic properties as given in CRD-C 18.[2]

The velocity at which a compressional wave travels through an isotropic solid is often used as a relative measure of the competency of the material. Compression wave velocities were determined on selected rock core samples by the method given in CRD-C 51.[2]

2.5 PETROGRAPHIC EXAMINATION

A limited petrographic examination was conducted on samples selected to be representative of the material received. The examination was limited to identifying the rock, determining general condition, identifying mineralogical constituents, and noting any unusual characteristics which may have influenced the test results.

2.6 STRENGTH TESTS

The unconfined, cyclic, triaxial, hydrostatic, and confined compression test specimens were prepared according to the American

Society for Testing and Materials and Corps of Engineers standard method of test for triaxial strength of undrained rock core specimens, CRD-C 147.[2] Essentially, the specimens were cut with a diamond blade saw, and the cut surfaces were ground to a tolerance of 0.001 inch across any diameter with a surface grinder prior to testing. Electrical resistance strain gages were utilized for strain measurements, two each in the axial (vertical) and horizontal (diametral) directions. Static Young's, bulk, shear, and constrained moduli were computed from strain measurements. Stress was applied with a 440,000-pound-capacity universal testing machine. The stress conditions are:

1. Unconfined strength, $\sigma_1 : \sigma_2 = \sigma_3 = 0$
2. Triaxial strength, $\sigma_1 : \sigma_2 = \sigma_3 \neq 0$
3. Hydrostatic stress, $\sigma_1 = \sigma_2 = \sigma_3$
4. Confined stress, $\sigma_1 : \sigma_2 = \sigma_3$, variable, to maintain $\epsilon_2 = \epsilon_3 = 0$

2.7 SHOCK RESPONSE

The shock-loading characteristics of the rock at relatively low dynamic pressures were studied by observing the action of a shock wave produced by the impact of a projectile on a rock specimen. The system, given in the Addendum to Appendix A, "System for Studying the Shock Response of Rock and Other Nonferromagnetic Materials at

Pressures Below 40 Kilobars," loads the sample in a one-dimensional state in approximately 1 μsec.

The Hugoniot equation of state was determined on selected samples in the pressure range of 50 to 500 kilobars by an explosive system consisting of a plane-wave lens and high explosive charge as given in the Addendum to Appendix A, "System for the Determination of the Hugoniot Equation of State of Rock and Grout."

CHAPTER 3

SERIES I TEST RESULTS

3.1 DIORITE

Core samples received from three of the holes were identified as diorite: soda diorite from Laramie and CR-19 and lime diorite from Hole CR-32. Detailed results are given in Appendixes B, C, and D; a summary of the results is given below:

Property	Hole Number			
	Laramie	CR-19 (top)	CR-19 (bottom)	CR-32[a]
Data, Appendix	B	C	C	D
Schmidt number	50.1	54.1	56.4	54.8
Specific gravity	2.72	2.82	2.88	2.76
Porosity, percent	0.0	0.0	0.1	0.1
Tensile strength, psi	1,400	1,130	1,350	1,440
Shear strength, psi	2,420	1,060	1,560	--
Compressive strength, psi	21,580	25,070	24,670	27,470
Compression wave velocity, fps	19,790	20,400	20,800	15,480
Shear wave velocity, fps	11,270	11,400	11,360	10,980

(Continued)

[a] Overall quality very poor due to fragmentation.

Property	Hole Number			
	Laramie	CR-19 (top)	CR-19 (bottom)	CR-32
Dynamic moduli, millions of psi				
Young's	11.8	12.4	13.7	9.6
Bulk	8.2	9.4	14.2	3.6[b]
Shear	4.5	4.9	5.1	4.5
Dynamic Poisson's ratio	0.26	0.28	0.34	0.06[b]
Static moduli, millions of psi				
Young's	11.8	13.7	13.8	12.0
Bulk	8.6	11.6	11.7	8.8
Shear	4.6	5.3	5.5	4.7
Static Poisson's ratio	0.26	0.30	0.30	0.27

[b] Doubtful result.

The material from two of the three diorite holes sampled, Laramie and CR-19, appeared to be very competent, relatively uniform rock with little fracturing or jointing. The lime diorite from Hole CR-32 was badly fragmented due to the presence of numerous horizontal, vertical, and steeply dipping fracture surfaces, almost all of which were present prior to drilling. The Laramie core was the coarsest grained and, surprisingly, the most uniform. The CR-19 core was slightly more competent than the Laramie core, but quite variable. Compressive strength ranged from 20,000 to 30,000 psi although the large variation is not evident in the averages reported above.

The soda diorite is apparently a very rigid rock as indicated by the high moduli and negligible hysteresis of the stress-strain curves. The lime diorite was significantly poor when compared with all other cores received from the Warren area. The indication of high quality by the basic tests reported above should not be construed as evidence of a competent material throughout. The entire length of samples received was highly fractured; locating sufficient core for test specimens was difficult. As indicated by the basic tests, the core which was not fractured was a relatively competent material.

3.2 GRANITE

Samples received from five of the holes, CR-4, -35, -39, -42, and -48, were identified as medium- to coarse-grained granite. The core from the lower depth of Hole 4 was identified as tonalite. Detailed results are given in Appendixes E through I; a summary of the results is given below:

Property	Hole Number CR-					
	4(top)	4(bottom)	35	39	42	48
Data, Appendix	E	E	F	G	H	I
Schmidt number	53.5	56.6	52.7	52.2	50.0	57.3
Specific gravity	2.63	2.69	2.69	2.71	2.67	2.66

(Continued)

Property	Hole Number CR-					
	4(top)	4(bottom)	35	39	42	48
Porosity, percent	0.0	0.0	0.1	0.6	0.4	0.4
Tensile strength, psi	1,120	1,380	870	815	780	1,200
Shear strength, psi	--	2,030	1,000	1,370	1,910	1,450
Compressive strength, psi	24,300	30,950	21,960	20,940	18,060	21,870
Compression wave velocity, fps	14,600	18,360	12,550	17,030	15,340	18,260
Shear wave velocity, fps	8,780	10,640	7,350	10,180	9,070	10,880
Dynamic moduli, millions of psi						
Young's	5.7	10.0	4.8	8.4	7.1	9.8
Bulk	2.1	5.0	3.1	3.7	3.4	5.0
Shear	2.7	4.3	1.9	3.7	3.1	4.2
Dynamic Poisson's ratio	0.05[a]	0.17	0.24	0.12	0.14	0.17
Static moduli, millions of psi						
Young's	10.0	10.6	7.9	7.9	10.0	9.7
Bulk	6.0	7.1	4.8	6.4	7.3	6.8
Shear	4.1	4.3	3.2	3.1	4.1	3.8
Static Poisson's ratio	0.22	0.25	0.22	0.29	0.27	0.26

[a] Doubtful result.

The granite from the five holes sampled is composed generally of quartz, plagioclase and potassium feldspars, and biotite with smaller amounts of hornblende, pyroxene, and several other minerals. The rock is quite similar from hole to hole, and possibly may all have been taken from the same igneous body. The tonalite from Hole 4 was obviously different in appearance and was apparently slightly more competent than the reddish granite. All of the rock tested appeared to be competent material, and relatively uniform in physical properties within drill holes and between holes.

The compressive strength of samples tested from Holes 35, 39, and 48 was unusually consistent for a rocklike material. The rock in Hole 42 was the most variable material reported above and also the least competent, due probably either to the small amount of montmorillonitic clay or the numerous small fractures present throughout the core. Most of the compression test specimens from all holes, but especially Hole 42, exhibited a slight plastic-elastic stress-strain relation associated with initial crack closing, followed by a steeper linear relation. The hysteresis loops were essentially closed; little residual strain was evident. The small fractures might also be the cause for apparently lower moduli determined dynamically, since the static moduli were determined under stress while the dynamic moduli were determined on unstressed specimens.

3.3 GNEISS

The cores received from Holes CR-10 and CR-15 were identified as gneiss. Gneiss is the rock name for a metamorphic rock that shows alternating layers of light- and dark-colored minerals. Detailed results are given in Appendixes J and K. A summary of the results is given below:

Property	Hole Number CR-				
	10 (top)	10 (bottom)	15 (top)	15 (middle)	15 (bottom)
Data, Appendix	J	J	K	K	K
Schmidt number	57.3	54.4	52.5	57.5	53.9
Specific gravity	2.63	2.73	3.06	2.69	2.93
Porosity, percent	0.4	0.4	0.0	0.0	0.0
Tensile strength, psi	1,360	1,030	2,260	1,140	2,220
Shear strength, psi	--	1,370	--	--	1,220
Compressive strength, psi	29,930	15,300	30,770	29,200	32,900
Compression wave velocity, fps	15,590	18,060	18,980	15,900	18,280
Shear wave velocity, fps	9,420	10,880	12,700	--	12,130

(Continued)

Property	Hole Number CR-				
	10 (top)	10 (bottom)	15 (top)	15 (middle)	15 (bottom)
Dynamic moduli, millions of psi					
Young's	6.9	10.0	15.2	--	13.5
Bulk	2.9	5.2	7.7	--	6.8
Shear	3.1	4.2	6.5	--	5.8
Dynamic Poisson's ratio	0.11	0.18	0.17	--	0.17
Static moduli, millions of psi					
Young's	8.8	9.3	14.7	11.8	14.4
Bulk	4.9	7.3	10.3	6.8	9.1
Shear	3.7	3.7	5.8	4.8	5.8
Static Poisson's ratio	0.20	0.27	0.26	0.21	0.24

The gneissic rock from the two holes sampled is apparently competent but quite variable material. Two distinct types of material were evident in the core received from Hole 10, a light-colored gneiss at the top or upper elevation, and dark banded rock in the lower depths. The light-colored rock had an unusually high compressive strength (approximately 30,000 psi) and Schmidt number (57.3) for a moderately dense material. Conversely, the banded material, although somewhat heavier and with a significantly higher velocity, yielded a compressive strength only half that of the light-colored rock due to failure along the bands.

Three types of material were evident in the core received from Hole 15: a dark amphibolite in the upper portion, a white pegmatite in the middle, and banded amphibolite and pegmatite in the lower. The range in individual compressive strength tests was rather large, 23,000 to 40,000 psi (Appendix K); however, the averages of the three groups were approximately equal. Significantly, the test results obtained on the white pegmatite, at the middepth in Hole 15, compare closely with the results obtained on the light-colored rock from the top of Hole 10. The relatively high tensile strengths indicated for the upper and lower elevations of Hole 15 were determined perpendicular to the banding; actually the shear strength (approximately 1,200 psi), determined with the banding, is more indicative of the lower failure stress level of the material. Stress-strain curves for rock from both holes show negligible hysteresis.

CHAPTER 4

SERIES II TEST RESULTS

4.1 LARAMIE CORE

The Laramie core was selected to represent the diorites for the Series II tests. Hydrostatic compression tests were conducted on three specimens, one each to pressures of 8,000, 20,000, and 36,000 psi. Triaxial tests were then conducted utilizing the same specimens at confining pressures equal to the hydrostatic pressures previously applied. Two confined compression tests were conducted on separate specimens, the confining pressure being applied to prevent lateral straining as axial load was applied by the piston in the triaxial chamber. Results are given in Appendix B. Young's, bulk, and constrained moduli may be compared for the unconfined (Series I) and confined (Series II) tests as follows:

	Moduli, millions of psi			
	Series I		Series II	
	Computed From	Result	Computed From	Result
Young's	Unconfined test	11.8	Triaxial test	12.2
Bulk	Poisson's ratio	8.6	Hydrostatic test	9.1
Constrained	Theory of elasticity	16.9	Confined test	16.3

Good correlation is, therefore, indicated between the unconfined and confined tests.

The Mohr envelope for the triaxial tests is apparently a straight line up to the 20,000-psi confining pressure level and then assumes a curvilinear relation with increased confining pressure. Pronounced shear planes developed in the specimens tested at 8,000- and 20,000-psi confining pressures; however, initial failure apparently occurred along a crystal face in the 36,000-psi test. Thus, the curvature of the envelope may be due to premature yielding along the crystal interface. The compression wave velocity was recorded during test to failure of two triaxial test specimens. The results indicated that the velocity increased initially under load, probably due to closure of small cracks, and then remained rather constant up to failure.

4.2 CR-42 CORE

The CR-42 core was selected to represent the granites for the Series II tests. Hydrostatic compression tests were conducted on three specimens, one each to pressures of 9,000, 18,000, and 36,000 psi. Triaxial tests were then conducted utilizing the same specimens at confining pressures equal to the hydrostatic pressures previously applied. Two confined compression tests were conducted on separate specimens, the confining pressure being applied to prevent lateral straining as axial load was applied by the piston in the triaxial chamber. Results are given in Appendix H. Young's, bulk, and

constrained moduli may be compared for the unconfined (Series I) and confined (Series II) tests as follows:

	Moduli, millions of psi			
	Series I		Series II	
	Computed From	Result	Computed From	Result
Young's	Unconfined test	10.0	Triaxial test	12.0
Bulk	Poisson's ratio	7.3	Hydrostatic test	5.8
Constrained	Theory of elasticity	14.4	Confined test	15.0

Significantly, the Young's modulus is lower for the unconfined test, and the bulk modulus higher, compared with the confined tests. A possible explanation is the closure of the small fractures under load. If the fractures close predominantly under initial load, as is usually the case, the unconfined Young's modulus would be lower, as it is, than the triaxial Young's modulus which is determined after the confining pressure has been applied. Also, the hydrostatic bulk modulus could be expected to be lower than the static bulk modulus which is computed at approximately one-half the ultimate strength in the unconfined test.

Due to the variability of the CR-42 core, two Mohr envelopes were constructed utilizing the results of the unconfined and triaxial

compression tests. The more competent material had an initial angle of shearing resistance of approximately 52 degrees, the less competent rock, 45 degrees. Also, the envelope of the less competent material appeared to be assuming a curvilinear relation at 36,000-psi confining pressure, the maximum available for these tests. The compression wave velocity was recorded during test to failure of two triaxial test specimens. As in the tests on the diorite core, the velocity increased slightly under load, probably due to closure of small cracks.

4.3 CR-10 CORE

The CR-10 core was selected to represent the gneiss for the Series II tests. Hydrostatic compression tests were conducted on three specimens, one each to pressures of 9,000, 18,000, and 36,000 psi. Triaxial tests were then conducted utilizing the same specimens at confining pressures equal to the hydrostatic pressures previously applied. Two confined compression tests were conducted on separate specimens, the confining pressure being applied to prevent lateral straining as axial load was applied by the piston in the triaxial chamber. Results are given in Appendix J. Young's, bulk, and constrained moduli may be compared for the unconfined (Series I) and confined (Series II) tests as follows:

	Moduli, millions of psi			
	Series I		Series II	
	Computed From	Result	Computed From	Result
Young's	Unconfined test	9.2	Triaxial test	12.0
Bulk	Poisson's ratio	6.5	Hydrostatic test	7.0
Contrained	Theory of elasticity	13.9	Confined test	15.0

Reasonably good correlation is indicated between the unconfined and confined tests.

The Mohr envelope for the triaxial tests is initially a straight line at an angle of shearing resistance of approximately 45 degrees. The envelope develops a pronounced curvilinear relation with increased confining pressure and appears to be approaching linearity at 36,000-psi confining pressure. However, the apparent approaching linearity should not be considered a Von Mises yield, but probably is the result of the bedding and stratification. Pronounced shear planes developed in the specimens along the bedding planes. The compression wave velocity recorded during test to failure of two triaxial test specimens increased slightly under load as for the diorite and granite specimens.

4.4 THERMAL PROPERTY TESTS

Thermal property tests on selected cores were added to the test program as testing was nearing completion. Thermal diffusivity, specific heat, and thermal conductivity tests were conducted on samples from four holes, CR-4, -15, -19, and -35. Test methods and results are given in Appendix L.

CHAPTER 5

SERIES III TEST RESULTS

5.1 TESTS

Equation of state tests were performed on the three rock types from the Warren Siting Area. A minimum of three low pressure tests (pressures less than 40 kilobars) and three high pressure tests (pressures to 400 kilobars) were conducted on each rock. The techniques and test equipment used in these tests are explained in the Addendum to the detailed results, Appendix A. A summary of the results is given below:

Core	Shock Velocity	Particle Velocity	Pressure	Specific Volume $\left(\frac{V}{V_o}\right)$
	mm/µsec	mm/µsec	kilobars	
Low Pressure Tests:				
Laramie	4.45	0.037	4.7	0.992
	4.99	0.139	18.7	0.972
	7.00	0.166	31.7	0.976
	6.10	0.263	43.4	0.957
CR-42	4.80	0.072	9.5	0.985
	5.00	0.090	11.9	0.982
	5.00	0.158	21.1	0.968
CR-10	4.15	0.081	9.2	0.980
	4.50	0.154	18.6	0.966
	3.22	0.268	28.9	0.930
	5.04	0.138	18.7	0.973

(Continued)

Core	Shock Velocity	Particle Velocity	Pressure	Specific Volume $\left(\frac{V}{V_o}\right)$
	mm/μsec	mm/μsec	kilobars	
High Pressure Tests:				
Laramie	4.42	0.71	95	0.851
	5.19	1.51	215	0.704
	5.80	2.17	340	0.610
CR-42	4.17	0.72	91	0.842
	5.51	1.48	216	0.724
	5.69	2.18	328	0.600
CR-10	4.03	0.74	89	0.832
	5.34	1.50	213	0.708
	5.79	2.18	333	0.603

5.2 DISCUSSION OF RESULTS

All three cores exhibited considerable data scatter due to the large grain size and material nonhomogeneity with respect to this type of test. The Laramie and CR-42 cores had Hugoniot elastic limits of 50 kilobars or more. The CR-10 core had an elastic limit of approximately 20 kilobars. The Laramie, CR-42, and CR-10 cores had elastic wave velocities of approximately 6.06, 6.03, and 5.68 mm/μsec, respectively. The second wave velocity, of course, is dependent upon the final pressure level attained in the material. All three high pressure tests for each material reached a final state which was still in the unstable or multiple wave region with the

ception of possibly the highest pressure test for CR-10. This particular data point appears to have just exceeded the multiple wave region.

Comparison of test results from the three test series is difficult due to the differences in test methods and properties determined. Moduli of deformation may be compared below as a matter of interest if one is mindful of the differences mentioned above.

	Moduli, millions of psi		
	Series I	Series II	Series III
State of stress	Unconfined	Confined	Confined
Rate of load	Static	Static	Shock
Modulus type	Young's	Constrained	One-Dimensional
Moduli for:			
Laramie	11.8	16.3	13.3
CR-42	10.0	15.0	9.3
CR-10	9.2	15.0	8.7

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The core received from the Warren Siting Area represented three types of rock: diorite, granite, and gneiss. Generally all samples received indicated relatively uniform, unweathered, hard rock with the exception of one hole, CR-32, which contained highly fractured lime diorite. Maximum crystal size of the other two diorite holes approached 2 inches, and that for the five granite holes, 1/2 inch. Stress-strain curves generally exhibited little hysteresis. Typically, basic properties for the rock from the nine competent holes would be approximately: (1) Unconfined compressive strength, 20,000 psi, (2) Specific gravity, 2.70, (3) Porosity, <1.0 percent, (4) Compression wave velocity, 15,000-17,000 fps, (5) Young's modulus, 10.0×10^6 psi.

Multiaxial tests indicated that bulk moduli would approximate 8.0×10^6 psi and constrained moduli, 15×10^6 psi. The maximum confining pressure available, 36,000 psi, did not allow definition of the Von Mises yield condition.

The low pressure shock tests indicated that the diorite and granite had Hugoniot elastic limits of 50 kilobars or more, and the gneiss an elastic limit of approximately 20 kilobars. The high pressure

tests for each material reached a final state which was still in the unstable or multiple wave region at the limit of the test equipment.

6.2 RECOMMENDATIONS

In order to better define the physical and mechanical behavior of the rock, it is recommended that the following additional tests be conducted on representative samples of the three materials: (1) Tests on specimens with joint planes under confining pressure to determine the yield envelope of the jointed rock. (2) Triaxial tests to approximately 150,000-psi confining pressure to determine the plastic yield limit of the intact rock. (3) Equation of state tests at pressures to approximately 600 kilobars to define the stable region and release adiabatic tests in the low pressure region to establish the shock unloading characteristics of the rock.

APPENDIX A

SERIES III TESTS

13 FEBRUARY 1969

Warren Siting Area: Series III Tests

Introduction

1. Series III equation of state tests were conducted on three cores from the Warren Siting Area. The low-pressure equation of state data were obtained using an induction wire technique in conjunction with a compressed-air gun facility. The high-pressure equation of state data were obtained using a pin technique in conjunction with a high explosive system. These techniques are explained in detail in the [illegible]. Plate 1 is a photograph of a typical specimen for both systems.

Material Description

2. a. Core No. 1 - Laramie.

(1) Rock type: soda diorite.

(2) Piece number and depth: 10 and 11; 69 to 70 ft.

(3) Density: 2.71 g/cc.

(4) Remarks: Grains were large (up to 1/2 in.) and nonuniform in size.

b. Core No. 2 - CR-42.

(1) Rock type: granite.

(2) Piece number and depth: 10 and 11; 85 to 87 ft.

(3) Density: 2.64-2.67 g/cc.

(4) Remarks: Large quartz crystals throughout specimen.

c. Core No. 3 - CR-19.

(1) Rock type: gneiss.

(2) Piece number and depth: 3 and 4; 56 and 59 ft.

(3) Density: 2.67-2.70 g/cc.

(4) Remarks: Large quartz crystals throughout specimen.

Warren Siting Area: Series III Tests

Low-Pressure Tests

3. Laramie (soda diorite).

a. Five tests were conducted on the Laramie core. SAMSO No. 2 and No. 5 were tested at pressures of approximately 4.? and 4.2 kilobars, respectively. The rise times of the particle velocity-time records ranged from 0.9 to 1.5 microsec. SAMSO No. 3 was tested at a pressure of approximately 18.8 kilobars with particle velocity-time rise times of 0.51 to 0.58 microsec. SAMSO No. 4 was tested at a pressure of approximately 31.7 kilobars and had rise times of 0.41 to 0.9 microsec. SAMSO No. 15 was tested at a pressure of approximately 43.4 kilobars and had a rise time of approximately 1.2 microsec.

b. Figures 1 and 2 show the pressure-particle velocity and pressure-strain relationship obtained from the five tests. Test Nos. 3, 4, and 15 yielded separate and distinct curves. The data from tests 2 and 5 were essentially the same and are, therefore, plotted as one set of data. Since the grains were large (up to 1/2 in.) and nonuniform in size, a great amount of material scatter was expected which would yield a considerable scatter in the data. However, the scatter should not be large enough to yield curves with as large a separation as indicated by tests 3 and 4. Material scatter could possibly account for the difference between tests 4 and 15. It is believed that possibly interface slippage is occurring in the lower pressure tests due to the large grain size causing lower shock velocities and, consequently, a lower pressure-particle velocity relationship. The shock velocity was less than the sonic velocity for tests 2, 3, and 5. Most of the records from these tests indicated some degree of instability. Apparently, tests 4 and 5 were conducted at pressures above this unstable region; therefore, the shock velocity was greater than the sonic velocity and increased with pressure.

c. The peak pressure point from tests 4 and 15 are shown on figures 7 and 8 along with the high-pressure test points. From an extrapolation of these points, it appears that the Hugoniot elastic limit is around 50 kilobars, although this was not determined.

4. CR-42 (granite).

a. Three low-pressure tests were conducted on cores from CR-42. Peak pressures of 9.5, 11.9, and 21.1 kilobars were obtained in SAMSO Nos. 6, 7, and 8, respectively. The rise times of the particle velocity-time records ranged from 0.6 to 0.8 microsec. The large quartz crystals caused considerable noise on the oscilloscope records (piezo-electric effect) which made the data reduction rather difficult. However, the reduced data from the three tests plotted essentially as one line on

the pressure-particle velocity (figure 3) and pressure-strain (figure 4) plots. The data indicate that the shock wave in the material is stable to 21 kilobars. Higher pressures were reached with the air gun; however, the noisy oscilloscope records made data reduction above 21 kilobars virtually impossible. It is believed that this problem can be overcome on future tests of materials containing large quartz crystals.

b. The peak pressure point from test No. 8 is shown on figures 9 and 10 along with the high-pressure test points. Extrapolation of the high-pressure points indicates that the Hugoniot elastic limit is around 50 kilobars.

5. CR-10 (gneiss).

a. Three low-pressure tests were conducted on cores from CR-10. Peak pressures of approximately 9.1, 29.0, and 18.6 kilobars were obtained in SAMSO Nos. 11, 12, and 14, respectively. The rise times of the particle velocity-time records ranged from 0.2 to 1.2 microsec. These specimens also had large quartz crystals throughout; however, the noise was not as significant as for the CR-42 cores. Figures 5 and 6 are plots of pressure-particle velocity and pressure-strain for this material. As can be noted from these plots, there is considerable scatter in the data. It is not quite as severe as for the Laramie core, and most of it can probably be due to material scatter or nonhomogeneity of the material.

b. Test Nos. 12 and 14 showed a definite second wave forming at approximately 18-19 kilobars indicating some sort of yielding. There is some question as to whether or not this is the Hugoniot elastic limit since this second wave is evidenced only on the second induction wire of each test. Since the first induction wire did not exhibit two waves, there is possibly more error associated with the second wave peak amplitude data point for test 14 shown on figures 5 and 6 than for the other points shown. Plate 2 is a photograph of the second induction wire oscilloscope record of test 12 showing the two-wave structure.

c. A test was also conducted on this material in which a quartz crystal was placed on the back of a 7.44-mm-thick specimen and impacted with a projectile having a velocity of approximately 1100 fps. The output of the quartz also indicated a two-wave structure with the first wave having an amplitude of approximately 18 kilobars.

d. The peak pressure points of first and second waves from test No. 12 are plotted on figures 11 and 12 along with the high-pressure test points. Extrapolation of the high-pressure points seems to confirm a low Hugoniot elastic limit although the data point around 90 kilobars has the largest uncertainty associated with it and, therefore, would influence the point of intersection of the two curves.

Warren Siting Area: Series III Tests

High-Pressure Tests

6. Three data points were determined on cores from the Warren Siting Area at three pressures as shown in table 1. Since existing granite data showed a precursor shock of around 50 kilobars, some alteration to the standard pin technique was necessary to prevent a precursor from shorting the time of arrival pins prior to the arrival of the main shock wave. This was accomplished by providing a known gap or standoff distance for the shock velocity pins to allow for the motion due to the precursor. Therefore, the shorting times of the pins correspond to the velocity of the main shock. This technique requires an assumption of the precursor shock level since no provision is made for measuring the elastic free surface velocity.

7. A simple computer program was used to compare the influence of the assumed precursor level on reducing the experimental data to the final data points. The precursor levels used ranged from 50 to 80 kilobars as shown in table 2 for soda diorite. These computations did not utilize a least squares fit of the experimental points and, therefore, do not extrapolate exactly to the final data in table 1. This assumption has a negligible effect on the two higher pressure tests, but is more pronounced on the data points at approximately 100 kilobars since this level is approaching the possible range of the precursor pressure.

8. The elastic precursor shock velocities as determined on the two higher pressure tests were used in the data reduction on all three tests. Some difference in the elastic precursor shock velocities is noted between these and the lower pressure air gun experiments; however, this is reasonable considering the large difference in peak pressure attained in the respective tests.

9. These data points are shown in graphical form in figures 7 through 12 along with an approximate fit throughout the pressure range.

Discussion

10. Equation of state data on polycrystalline rocks typically show significant scatter; for example, the work by Stanford Research Institute.* The precursor level ranged from 28 to 58 kilobars for anorthosite. Additional data points would thus be desirable for the rocks tested and would increase the confidence level of a curve fitted to the data for use

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* Ahrens, T. J., Rosenberg, J. T., and Ruderman, M. H., "Dynamic Properties of Rocks," DASA 1868, 30 September 1966, Stanford Research Institute.

in free-field codes. The assumption of a precursor level for these rocks is not considered to be significant except at final pressures of around 100 kilobars; however, an extension of the pin technique is being prooftested for use in two-wave regions which should eliminate the necessity of this assumption providing simultaneous measurements on both shock waves.

11. Since in this region the second wave travels at subsonic velocity depending on pressure, provision must be made for measuring this velocity. In addition, the locus of the Hugoniot elastic limit must be known in order to calculate the final Hugoniot point.

12. The magnitude of four variables, namely, elastic precursor and second-wave shock velocity and precursor and second-wave particle velocity, must be determined experimentally. The method to be used incorporates the principles of the inclined mirror-high-speed photography method modified to the use of self-shorting pins and presently used electronics.

13. The necessary data will be obtained as follows. One set of pins will be used to determine precursor velocity based on transit time through the sample. When the precursor overtakes the sample free surface, this surface is accelerated to velocity $u_{f.s._1}$. This free surface motion will be measured by a portion of a group of pins placed at small incremental distances from the surface. As the second shock eventually overtakes the free surface traveling at $u_{f.s._1}$, it accelerates the free surface to velocity $u_{f.s._2}$ of which this free surface motion will be measured by the remainder of the free surface pins. On an x-t plot the free surface velocities will intersect at the point that represents the arrival of the second wave at the free surface. This x, t point yields the shock velocity of the second wave. The impedance mismatch method is used to calculate the necessary Hugoniot information remaining based on these experimental data.

14. A high explosive flying plate technique is being prooftested and should enable the Waterways Experiment Station to extend the capability of this system by several hundred kilobars.

15. The compressed-air gun system and techniques are continually being modified to enhance the research capability of the system. The projectiles are being modified to aid in increasing the maximum velocity capability and, therefore, increasing maximum pressure capability. Projectile velocities are being measured more accurately. A technique for measuring planarity of impact is being investigated. An investigation

is being conducted to determine the feasibility of sputtering or vacuum deposition of a thin film to replace the small induction wires. Also, the technique of using quartz gages to measure or monitor the pressure-time profile in rock specimens is being investigated.

Summary

16. Equation of state tests were performed on three cores from the Warren Siting Area. A minimum of three low-pressure tests (pressures less than 40 kilobars) and three high-pressure tests (pressures to 400 kilobars) were conducted on each core. The techniques and test equipment used in these tests are explained in the addendum hereto.

17. All three cores were susceptible to considerable data scatter due to the large grain and material nonhomogeneity. The Laramie and CR-42 core had Hugoniot elastic limits of 50 kilobars or more. The CR-10 core had an elastic limit of approximately 20 kilobars. The Laramie, CR-42, and CR-10 cores had elastic wave velocities of approximately 6.06, 6.03, and 5.68, respectively. The second wave velocity, of course, is dependent upon the final pressure level attained in the material.

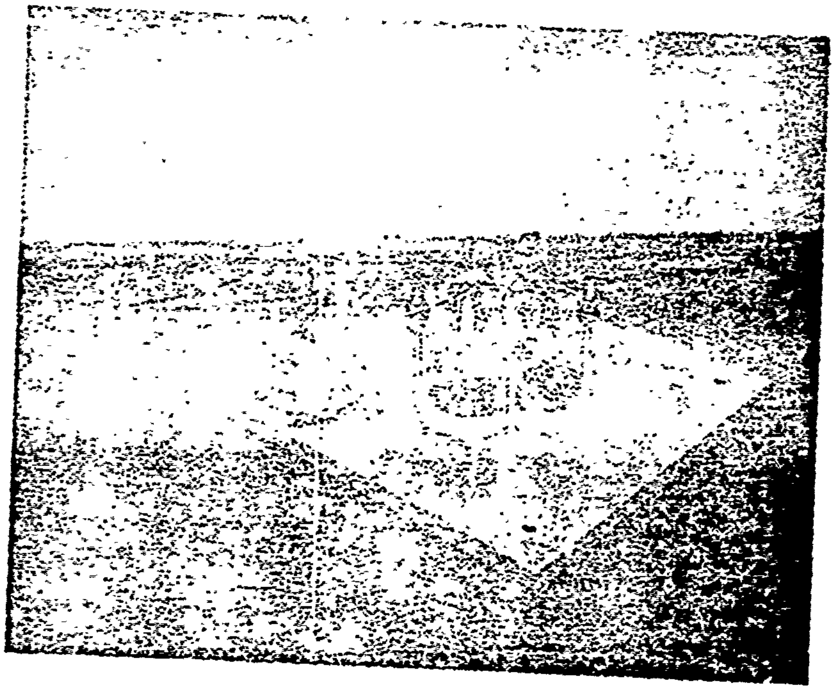
18. All three high-pressure tests for each material reached a final state which was still in the unstable or multiple wave region with the exception of possibly the highest pressure test for CR-10. This particular data point appears to have just exceeded the multiple wave region.

TABLE I

Specimen Description and Density (g/cc)	Assumed Hugoniot Elastic Limit: Pressure (kilobars)	Assumed Hugoniot Elastic Limit: Particle Velocity (mm/μsec)	Assumed Hugoniot Elastic Limit: $\frac{V_E}{V_o}$	Elastic Velocity (mm/μsec)	Final State: Shock Velocity (mm/μsec)	Final State: Particle Velocity (mm/μsec)	Final State: Pressure (kilobars)	Final State: $\frac{V}{V_o}$
Soda Diorite	50	0.304	0.950	6.06	4.42	0.711	95.1	0.851
2.71	50	0.304	0.950	6.06	5.19	1.51	215	0.704
	50	0.304	0.950	6.06	5.80	2.17	340	0.610
CR-42	50	0.314	0.948	6.03	4.17	0.722	91.2	0.842
2.64	50	0.314	0.948	6.03	5.51	1.48	216	0.724
	50	0.314	0.948	6.03	5.69	2.19	329	0.600
CR-10	50	0.330	0.942	5.68	4.03	0.735	89.4	0.832
2.57	50	0.330	0.942	5.68	5.34	1.50	213	0.708
	50	0.330	0.942	5.68	5.79	2.18	333	0.603

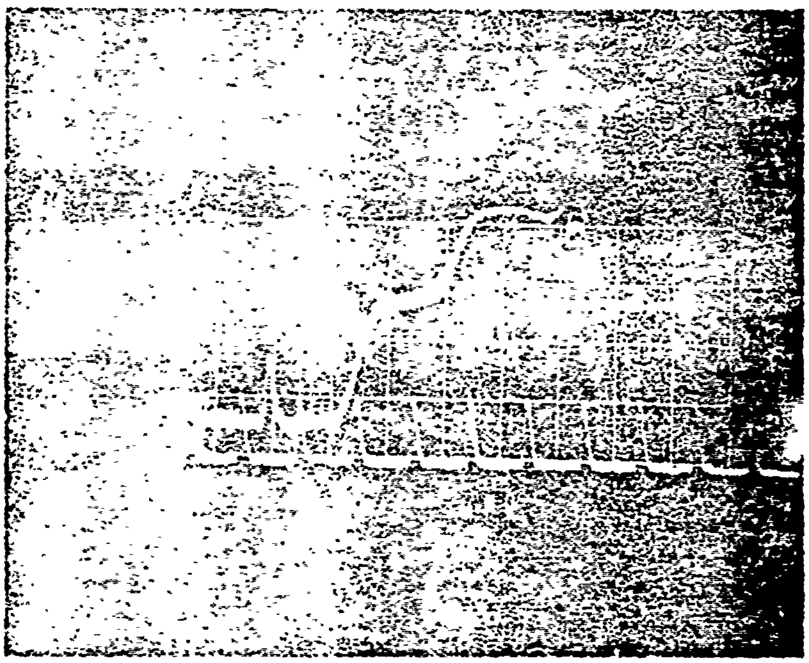
TABLE 2

Specimen Description and Density (g/cc)	HEL Pressure (kilobars)	Final State		
		Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kilobars)
Soda Diorite 2.71	50	5.55	0.67	102
	60	5.46	0.68	102
	70	5.30	0.68	101
	80	4.96	0.69	99.5
Soda Diorite 2.71	50	5.10	1.51	213
	60	5.08	1.52	213
	70	5.05	1.52	212
	80	5.04	1.53	212
Soda Diorite 2.71	50	5.79	2.17	339
	60	5.78	2.17	339
	70	5.78	2.18	338
	80	5.78	2.18	337



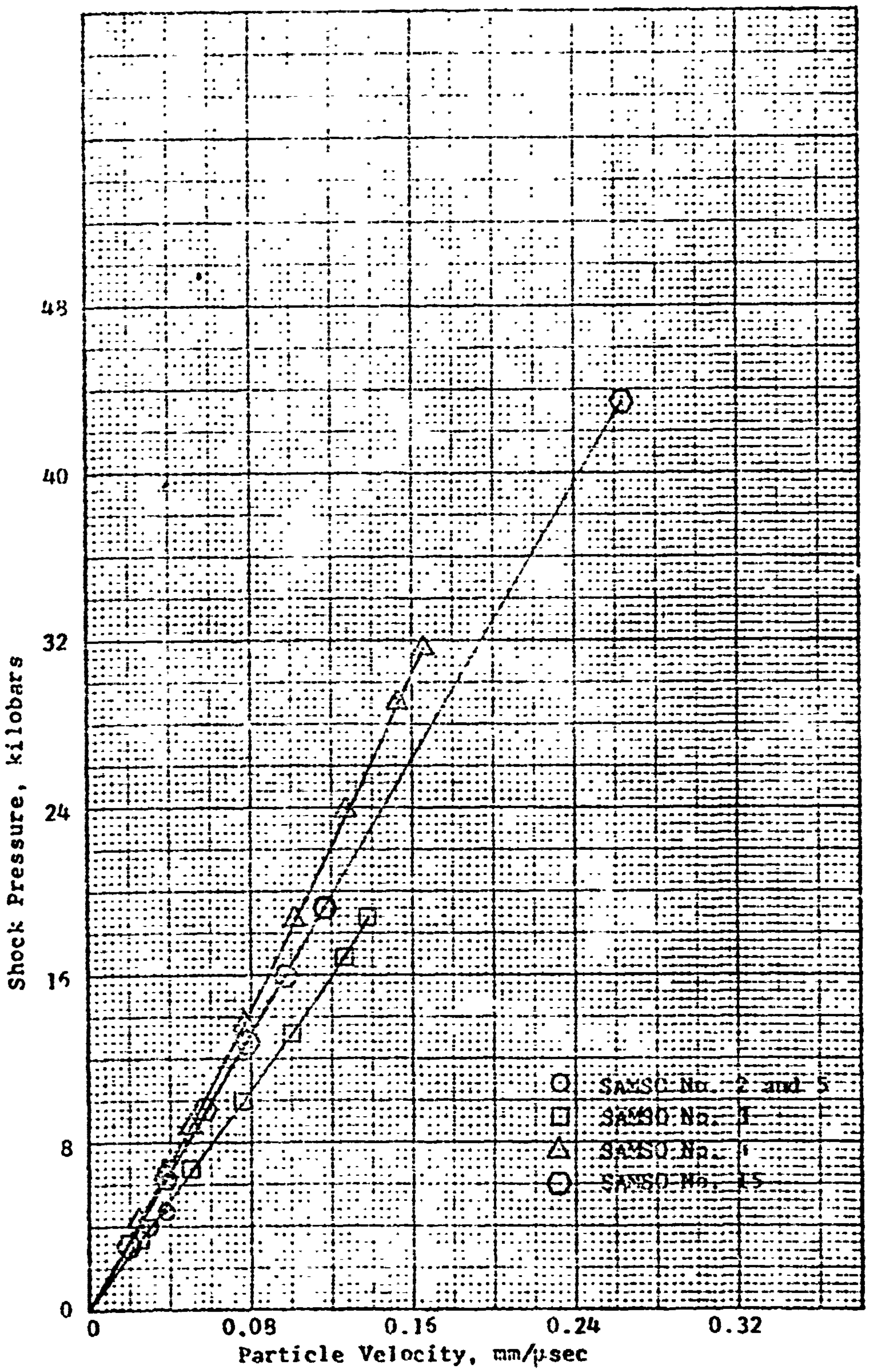
Typical specimen for both low-pressure and high-pressure experiments.

PLATE 1



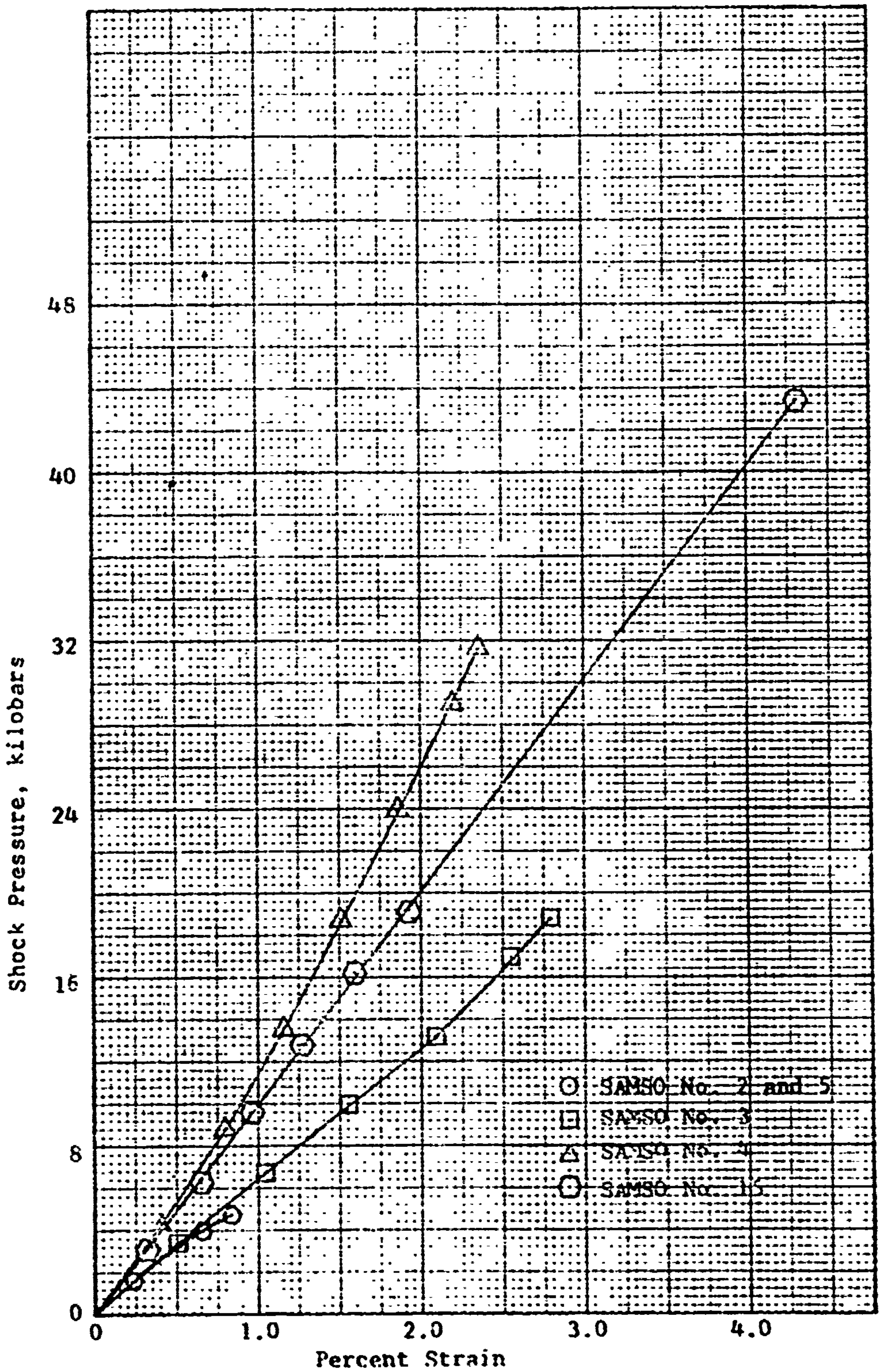
Induction wire record indicating two-wave structure.

PLATE [illegible]



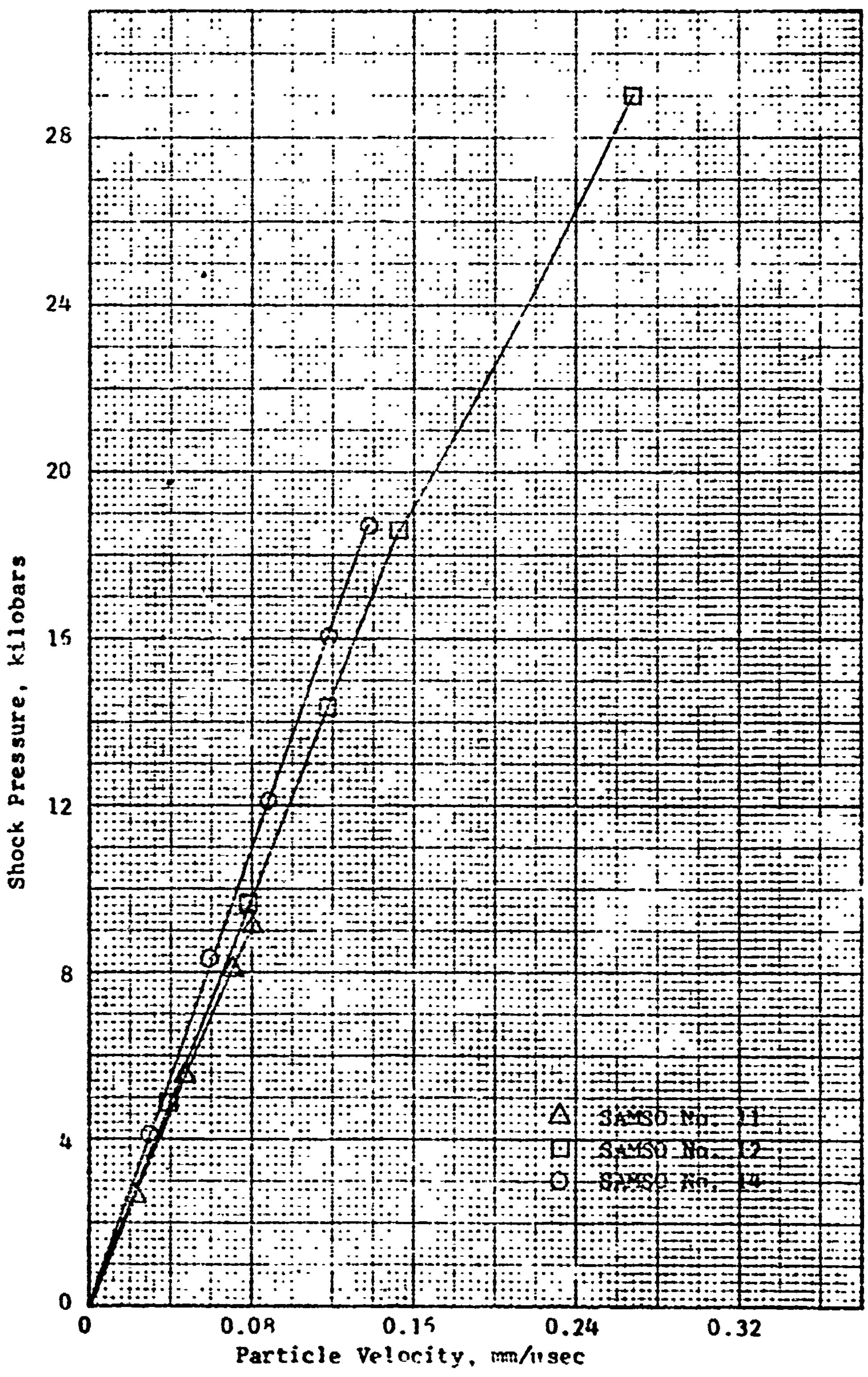
PRESSURE VS PARTICLE VELOCITY
SAMSO LARAMIE

FIGURE 1



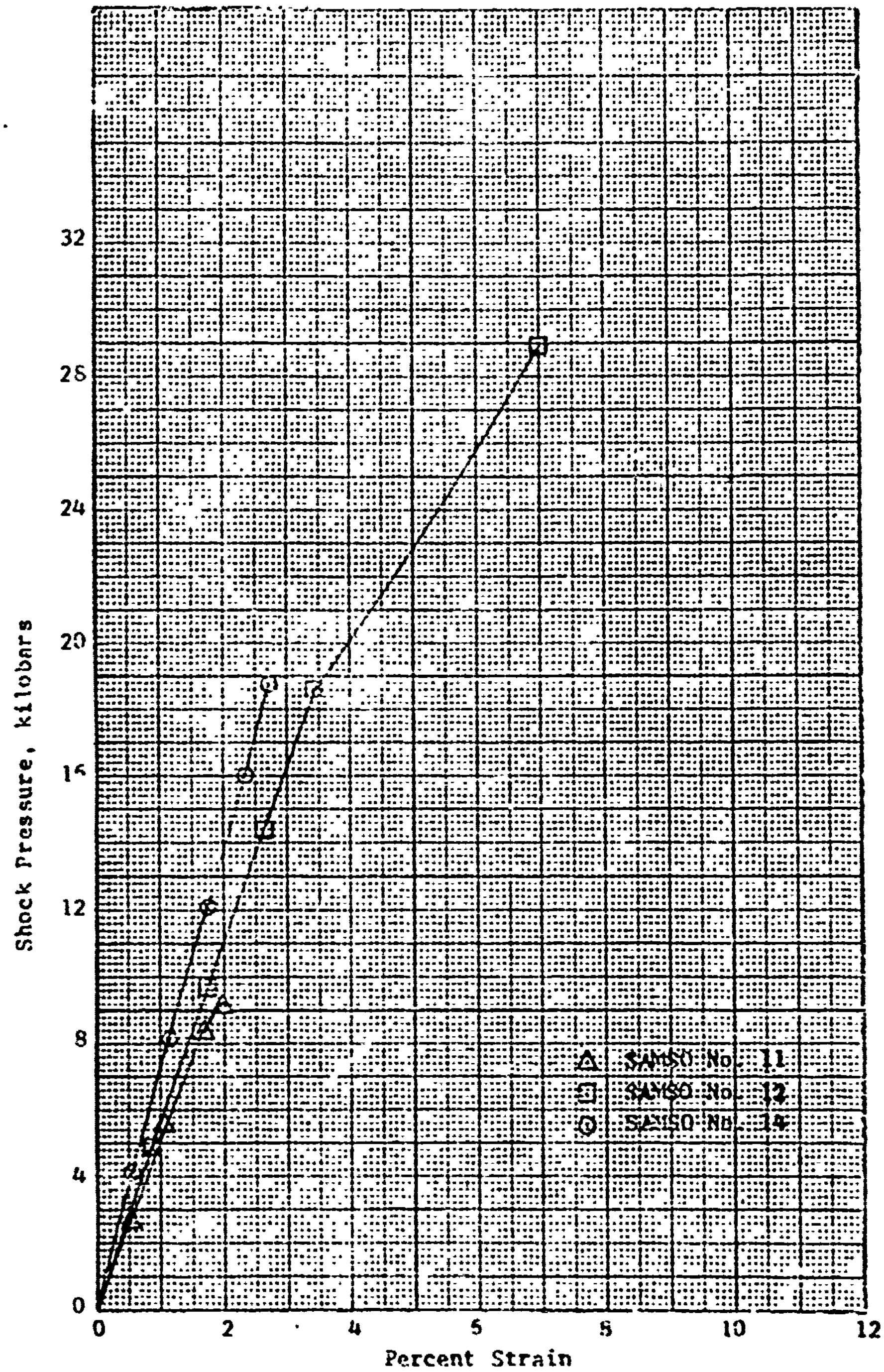
PRESSURE VS STRAIN
SAMSO LARAMIE

FIGURE 2



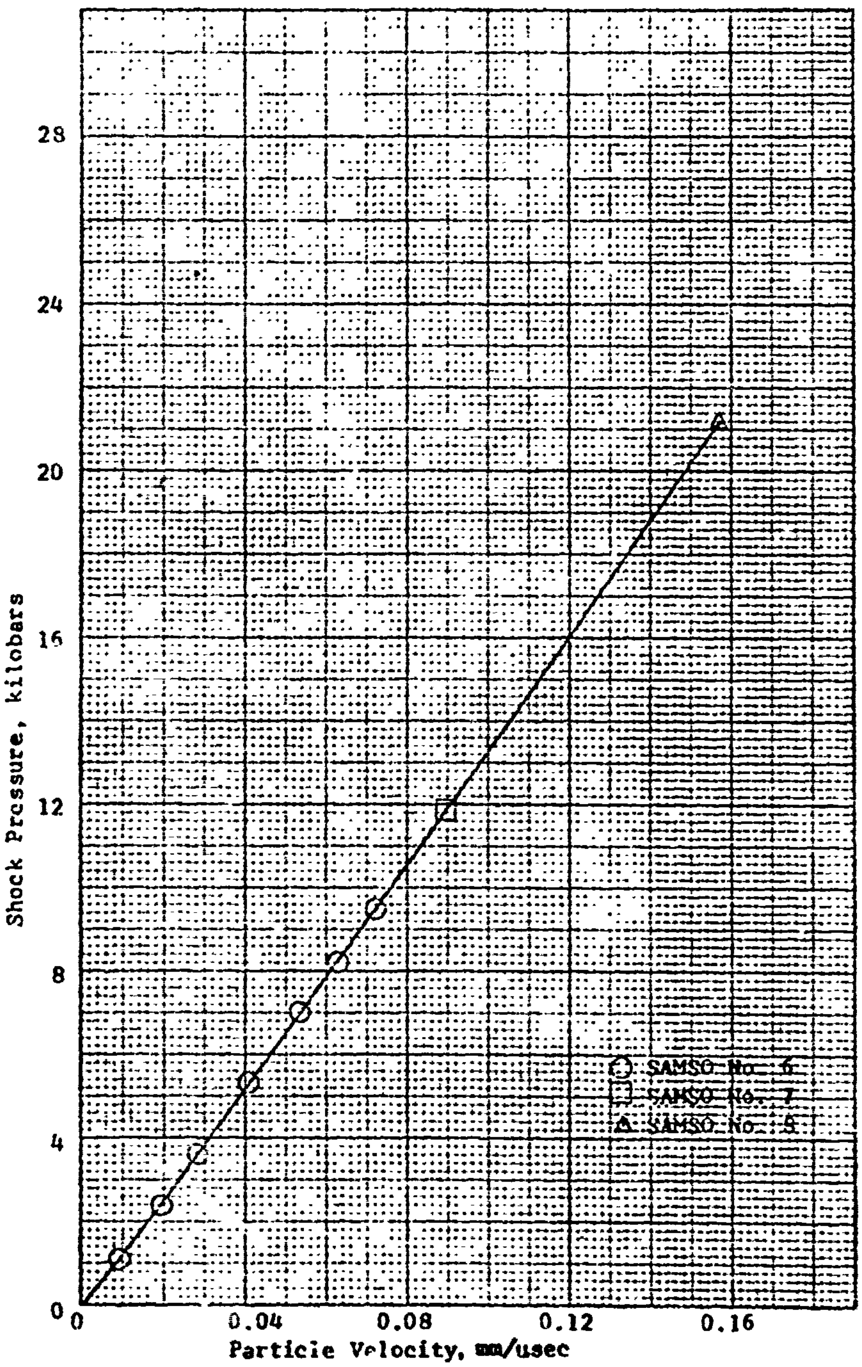
PRESSURE VS PARTICLE VELOCITY
SAMSO CR-10

FIGURE 3



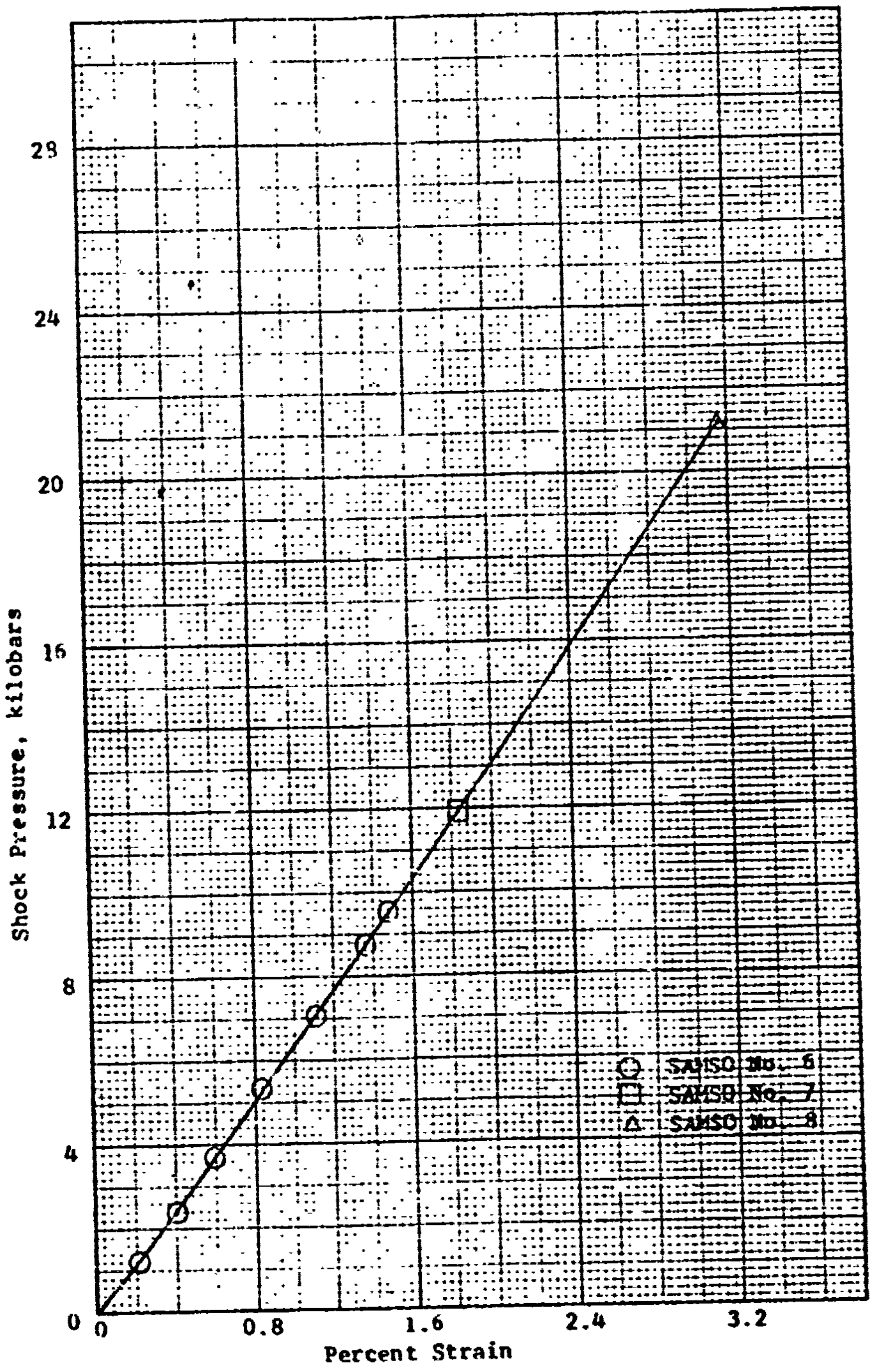
SHOCK PRESSURE VS STRAIN
SAMSO CR-10

FIGURE 4



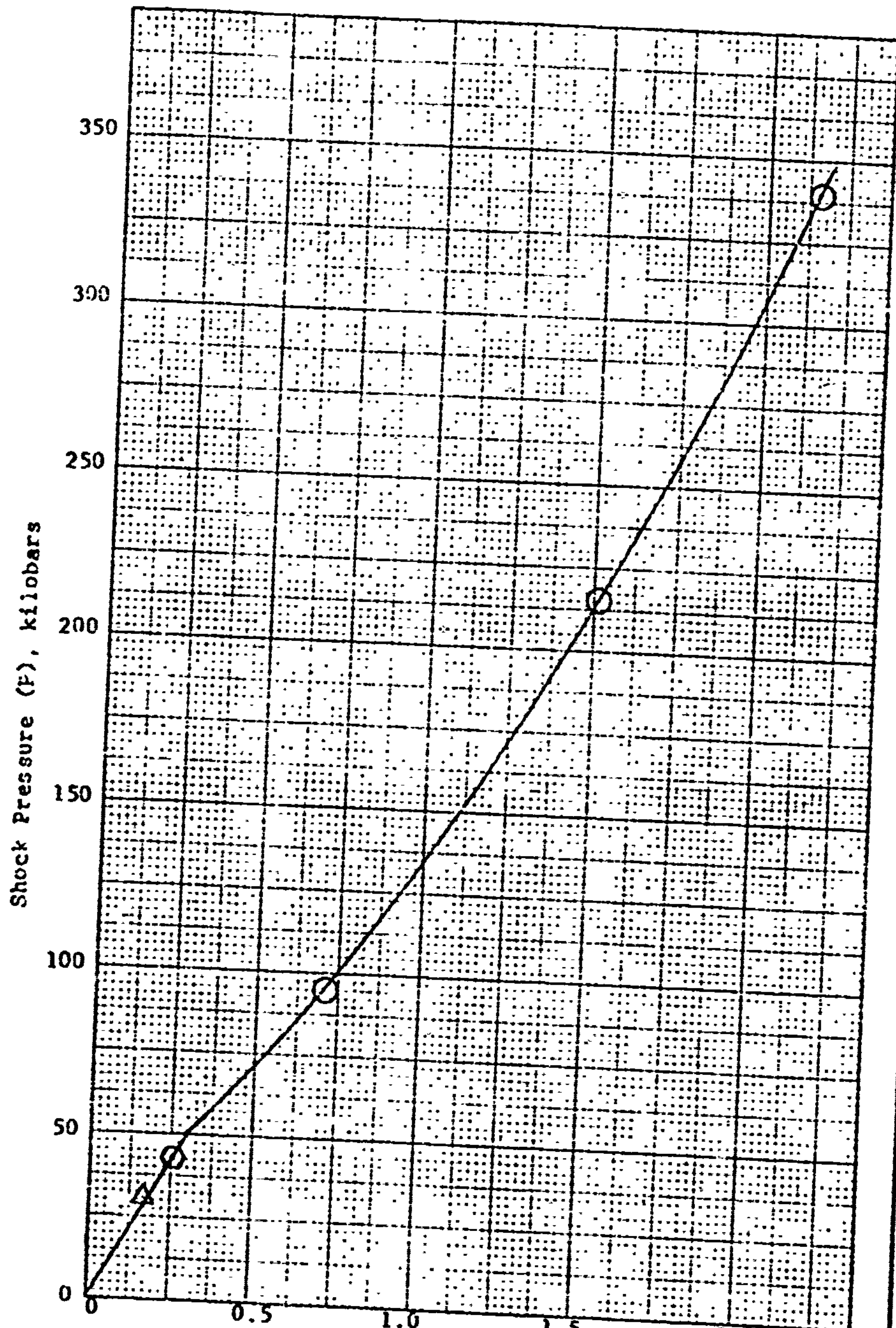
PRESSURE VS PARTICLE VELOCITY
SAMSO CR-42

FIGURE 5



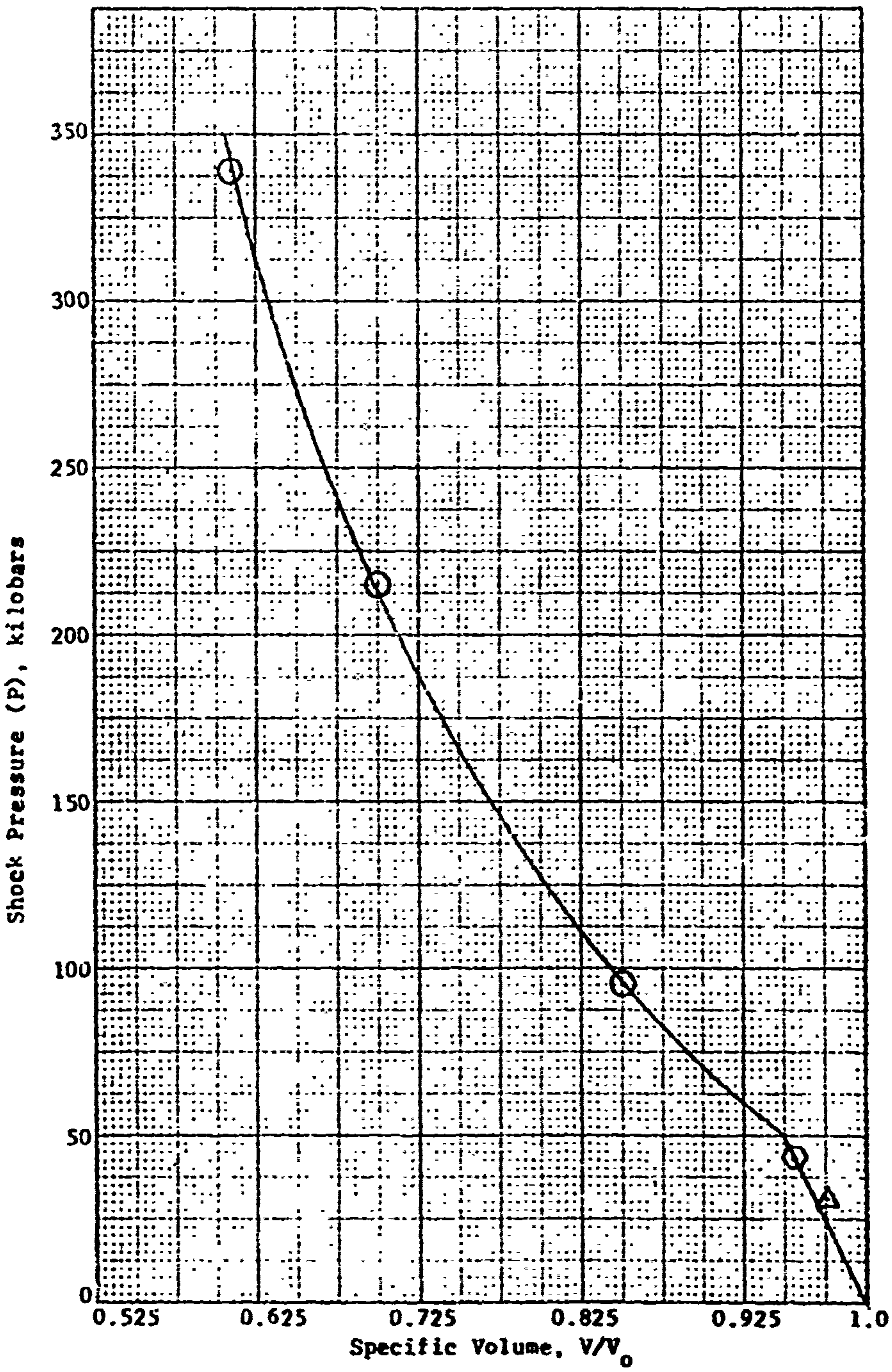
PRESSURE VS STRAIN
SAMSO CR-42

FIGURE 6



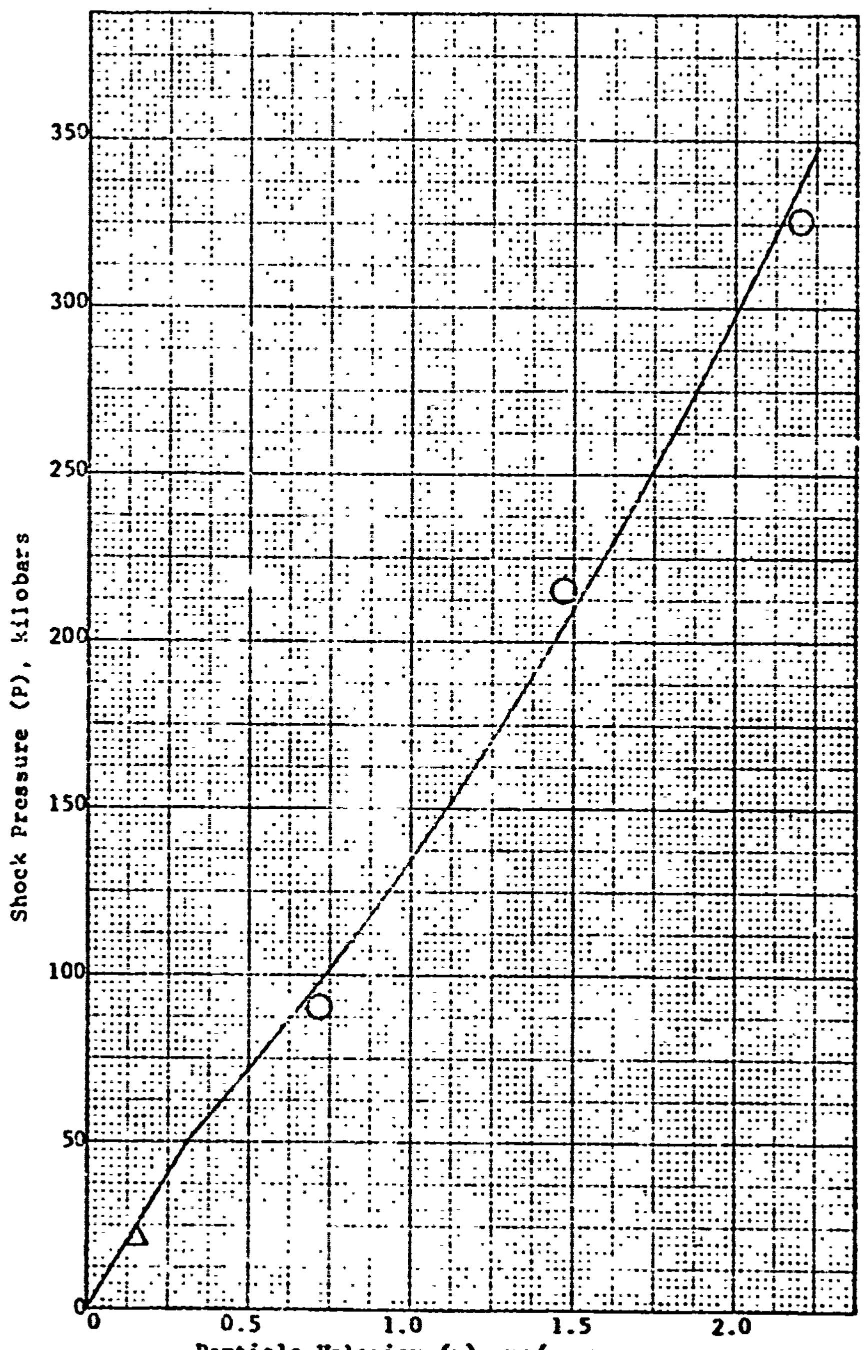
SHOCK PRESSURE VERSUS PARTICLE VELOCITY
SAMSO LARAMIE

FIGURE 7



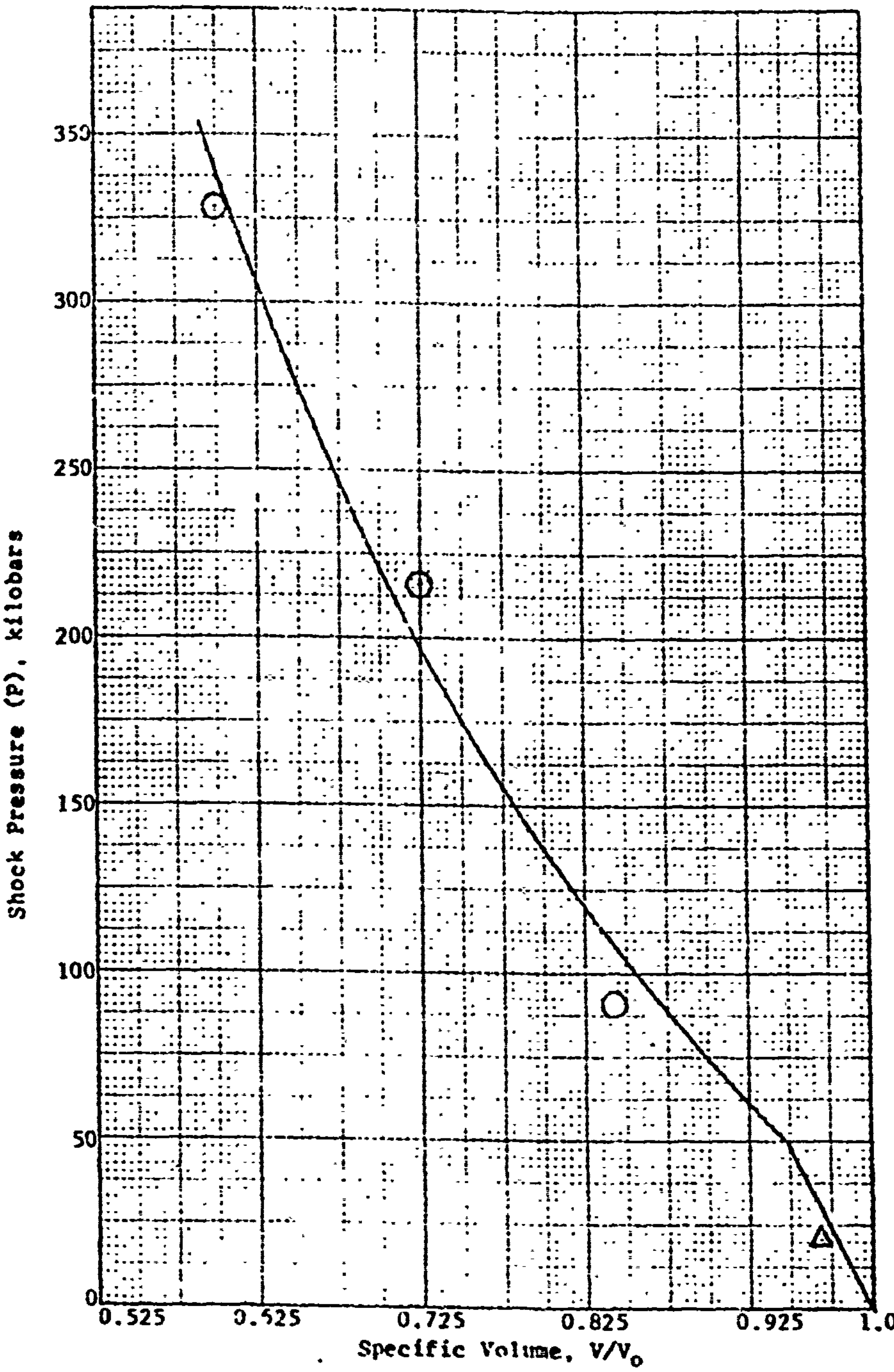
HUGONIOT EQUATION OF STATE
SAMSO LARAMIE

FIGURE 8



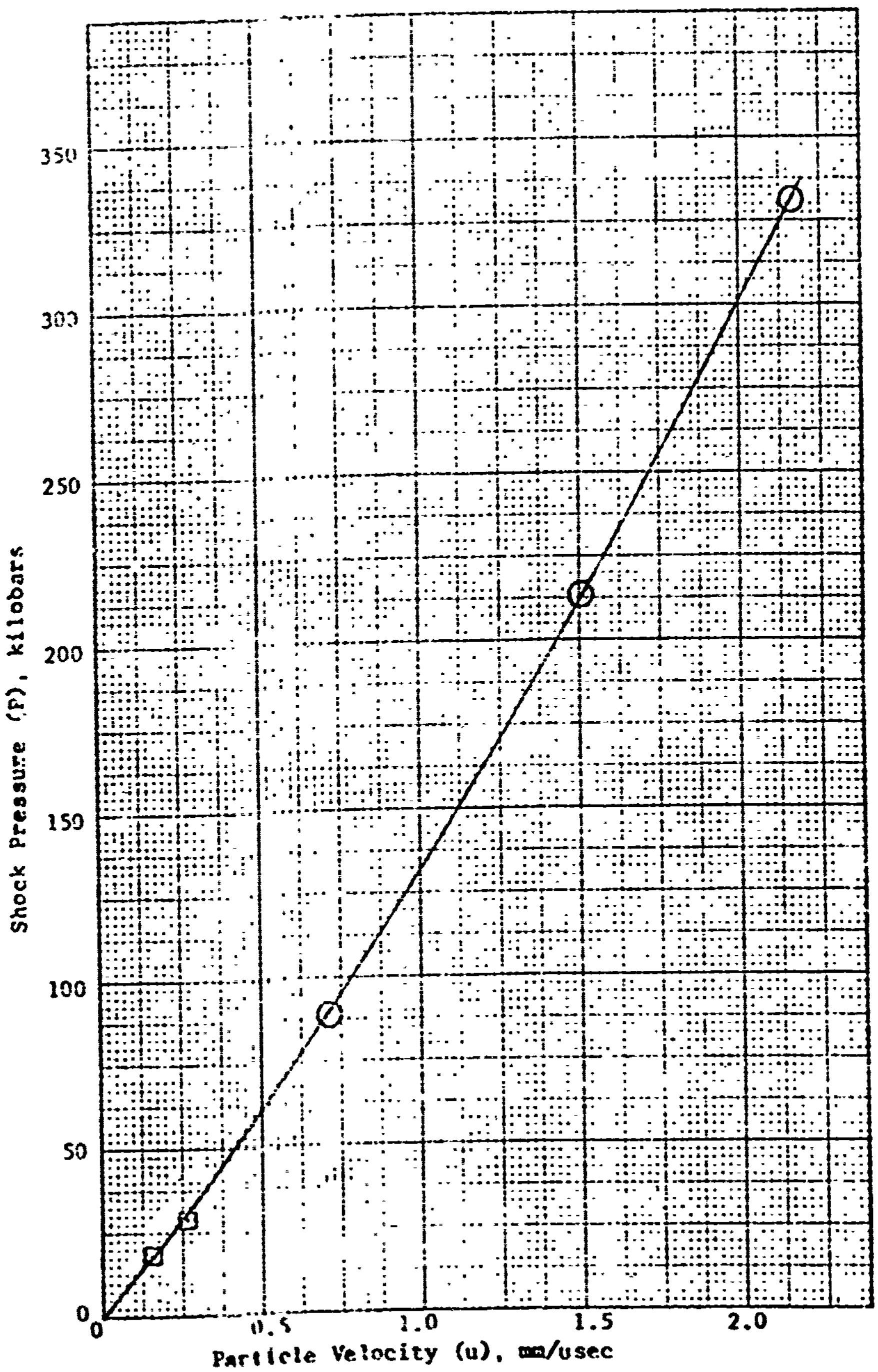
SHOCK PRESSURE VERSUS PARTICLE VELOCITY
SAMSO CR-42

FIGURE 9



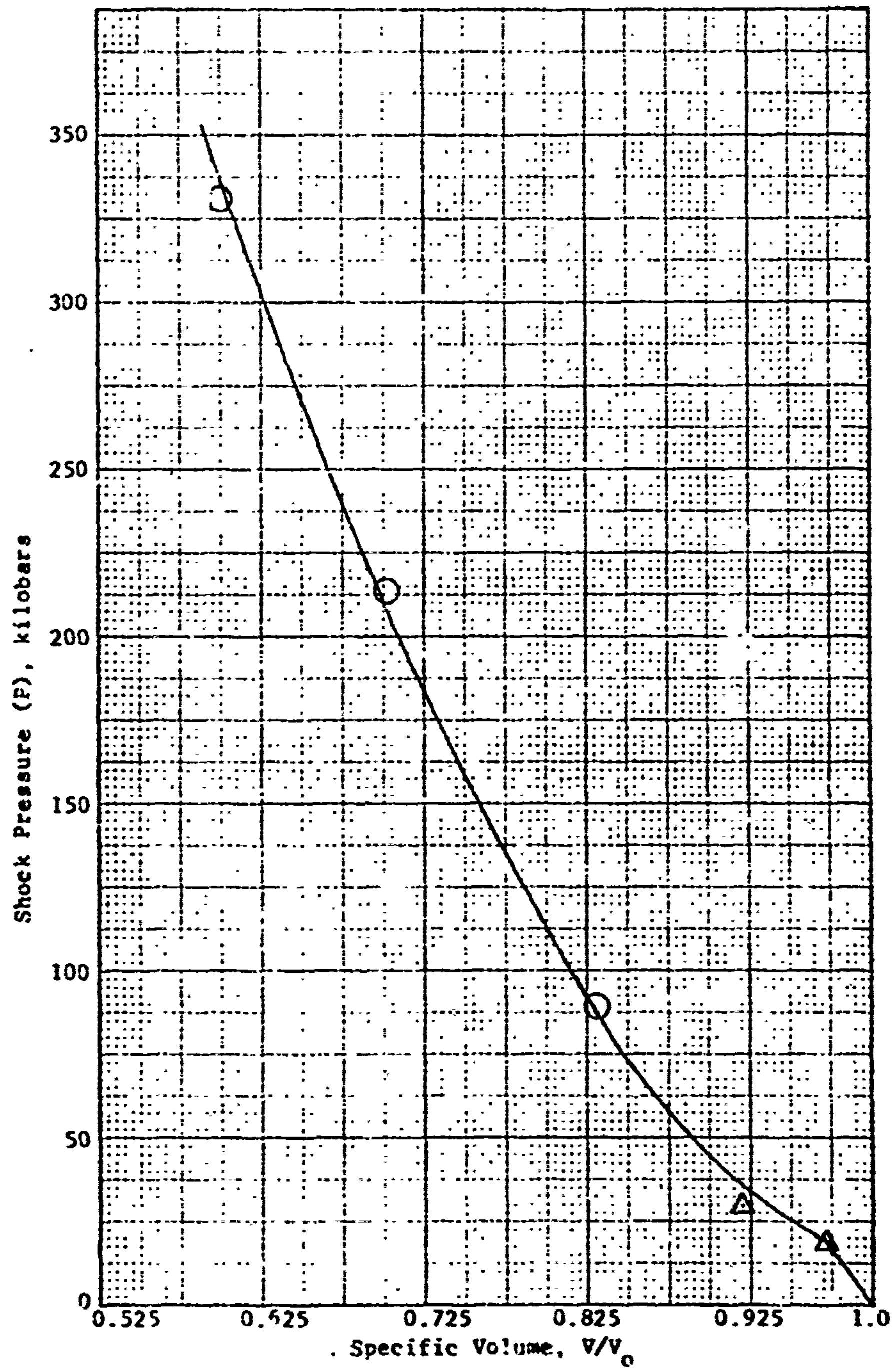
HUGONIOT EQUATION OF STATE
SAMSO CR-42

FIGURE 10



SHOCK PRESSURE VERSUS PARTICLE VELOCITY
SAMSO CR-10

FIGURE 11



HUGONIOT EQUATION OF STATE
SAMSO CR-10

FIGURE 12

ADDENDUM: DESCRIPTIONS OF

SYSTEM FOR STUDYING THE SHOCK RESPONSE OF ROCK AND OTHER NONFERROMAGNETIC MATERIALS AT PRESSURES BELOW 40 KILOBARS

AND

SYSTEM FOR THE DETERMINATION OF THE HUGONIOT EQUATION OF STATE OF ROCK AND GROUT

Warren Siting Area: Series III Tests

System for Studying the Shock Response of Rock and Other Nonferromagnetic Materials at Pressures Below 40 Kilobars

1. The Waterways Experiment Station (WES) has developed a system for continuous measurements of both the velocity of propagation of a shock wave and particle velocities in rock and other nonferromagnetic materials from the passage of a shock wave produced by a flat-plate impact. A stress-strain relationship is deduced from the wave and particle motion data. The system has an upper limit of approximately 40 kilobars.

2. The experimental method is primarily based on a technique used by Frasier and Karpov for directly measuring the particle velocity in a material. In this technique a fine wire is embedded in the material and placed in a magnetic field. Any subsequent movement of a portion of the wire which cuts the magnetic-flux lines produces an electromotive force (e) proportional to the instantaneous velocity as shown in the following equation:

$$e = \beta l v$$

where

β = the magnetic field strength,

l = the length of wire cutting the flux lines,

v = the velocity of the wire (particle velocity).

3. Several wires are placed in a test specimen and the voltages monitored on oscilloscopes and recorded on photographs. The velocity

of propagation can be determined from the initial rises of the voltage signals from the induction wires.

4. The specimen is mounted at the end of the compressed-air gun barrel in a magnetic field and the barrel evacuated to approximately 15 microns. The stress waves will be produced by impacting the specimens with an aluminum projectile. Impact velocities can be obtained up to 1200 ft/sec.

5. The final state behind the stress wave is determined by the application of the conservation equations. Conservation of mass and momentum across the shock front requires that:

$$\rho_o U_s = \rho_1 (U_s - U_{p1}) \qquad \text{(Conservation of mass)}$$

$$P_o + \rho_o U_s^2 = P_1 + \rho_1 (U_s - U_{p1})^2 \qquad \text{(Conservation of momentum)}$$

where

U_s = shock velocity,

U_{p1} = particle velocity behind the shock wave,

P_o = initial pressure,

ρ_o = initial density

the pressure behind the shock wave $\qquad P_1 = \rho_o U_s U_{p1} + P_o$

and the corresponding strain $\qquad e_1 + 1 - \rho_o/\rho_1 = U_{p1}/U_s$

These equations are based on the assumption that an equilibrium state of stress is reached behind the shock wave. In this simple form, they are valid only in the region of uniaxial strain. These equations correspond to the Hugoniot or the locus of shocked-end states reached.

25 January 1968

System for the Determination of the Hugoniot
Equation of State of Rock and Grout

The Waterways Experiment Station (WES) has the facility and capability to perform Hugoniot equation-of-state studies for rock and rock-matching grout over the pressure range of 50 to 500 kilobars. A number of shock-indicating pins are embedded in the specimen to measure the shock-wave velocity and another group is arranged over the free surface of a driver plate of known equation of state to measure the free-surface velocity. When these pins are struck by a shock, fast-rising pulses are produced which are displayed on high-speed oscilloscopes. The shock is produced in the material using an explosive system consisting of a plane-wave lens and a high-explosive charge. The shock and free-surface velocities are derived from the known pin spacing and the arrival times of the pulses as taken from the oscilloscope traces. Using the velocity data, the pressure and specific volume can be computed by means of the Rankine-Hugoniot equations.

In the test system, the pins which serve as the shock-arrival indicators comprise an outer coaxial conductor and an inner conductor, and have a cap on one end and a shielded cable on the other. The shock wave closes the pin by compressing the cap against the inner conductor, producing a short circuit which discharges a resistor-capacitor (RC) combination in the pulse-forming network. Each RC combination is given one of two polarities and pulse heights, and any one of four decay times to allow identification of a particular pin. The outputs from RC networks are recorded on high-speed oscilloscopes.

If the ambient density, shock velocity, and particle velocity are known, the pressure and specific volume of the shocked specimen can be determined from the following equations:

$$P_1 = \rho_o U_p U_s$$

$$V_1/V_o = 1 - U_s/U_p$$

where

U_s = the velocity of the shock wave

U_p = the particle velocity

ρ_o = the density of the ambient material

$V_o = 1/\rho_o$ = the specific volume of the ambient material

$V_1 = 1/\rho_1$ = the specific volume of the material behind the shock front

The shock velocity is determined directly by embedding pins at known distances in the specimen; these distances, along with the arrival times, can be used to compute the velocity.

The particle velocity is indirectly inferred from the free-surface velocity of the driver plate. This approximation is derived on the basis of the interaction of the shock wave with the rarefaction wave which is formed at the free surface and which propagates back into the shocked specimen. This interaction causes the free surface to move with a velocity which is the sum of the particle velocity of the shock and the particle velocity of the rarefaction wave. It has been shown that the two particle velocities are very nearly equal; hence, the particle velocity of the shock can be approximated by taking one-half the value of the measured velocity of the free surface (U_{fs}):

$$U_p = 1/2\ U_{fs}$$

The free-surface velocity is measured on a surface located midway between the first and last shock-velocity pins since the shock velocity will be an average value due to attenuation of the shock in passing through the specimen, whereas the free-surface velocity will not be appreciably attenuated by the air.

As with other high-explosive methods for determining the Hugoniot equation of state, only one point on the pressure-specific volume curve is obtained for each test. However, it should be noted that with the WES system data can be obtained from three materials in one test.

APPENDIX B

DATA REPORT - LARAMIE CORES

16 AUGUST 1968

WARREN SITING AREA

Core No. 1 (Laramie)

1. Twenty pieces of core were received from the Wyoming site, designated "Laramie" core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
B	1	60
B	2	61
B	3	62
B	4	63
B	5	64
B	6	65
B	7	66
B	8	67
B	9	68
B	10	69
B	11	70
B	12	71
B	13	72
B	14	73
B	15	74
A	16	17
A	17	18
C	18	151
C	19	152
C	20	153

2. The hole from which the core was taken was located in Albany County, Wyoming, longitude 105° 26.5', latitude 41° 31.5', township 18N, range 72W, section 23. All core was drilled vertically. Specimens were cut as required for the various tests; each segment of the specimen was given a letter designation signifying the section cut; for example, specimen 17a was the first test piece cut from specimen 17.

Warren Siting Area: Core No. 1 (Laramie); Sample A; Series I

Results

1. Only two tests were conducted on sample A, one compressive strength test and a petrographic examination.

Compressive strength

2. The stress-strain curve for the compressive strength test of specimen 17a is given in plate 1. A strength of 20,100 psi was indicated.

Petrographic examination

3. Fifteen feet of NX core from three depths from hole No. 1, Project S-11, 100, Albany County, Wyoming, was received on 19 March 1968. The core is identified below:

CD Serial No.	Length, ft	No. of Pieces	Depth, ft
WYO-1 DC-1(A)	2	2	17.0 - 18.9
WYO-1 DC-1(B)	14.5	15	60.5 - 75.0
WYO-1 DC-1(C)	2.5	3	150.5 - 153.0

4. All of the sample appeared to be homogeneous. The petrographic sample was taken from the 18.2-ft depth and was 2.7 in. long.

5. a. The 2-3/4-in. core was sawed axially. One of these sawed surfaces was polished and photographed.

b. A thin section, made from the other half of the piece, was examined with a polarizing microscope.

c. A composite sample of the 2-3/4-in. length was ground to pass a No. 325 sieve. A tightly packed portion of this powder was examined by X-ray diffractometry using nickel-filtered copper radiation.

d. The polished surface and fracture surfaces were examined with a stereomicroscope.

e. Some of the powdered rock was examined as an immersion mount with a polarizing microscope to determine the refractive index of the plagioclase feldspar.

6. The material examined is a medium dark gray (N 4)[1] coarse-grained igneous rock (photograph 1) composed largely of black and green

[1]The Rock Color Chart Committee, Rock Color Chart, National Research Council, Washington, D. C., 1948.

minerals. It is estimated that 80 percent or more of the rock is plagioclase feldspar; there are small amounts of chlorite and of other greenish mica and even smaller amounts of calcite, quartz, and opaque minerals, probably pyrite, leucoxene, and hematite. Optical determinations of refractive index and of extinction angles indicated that the composition of the plagioclase is about Ab_{56} An_{44}, and it is therefore andesine.

7. Examination of the thin section shows that the rock suffered some deformation and fine fracturing. These fractures are now filled with a variety of materials, mostly micaceous. There is no pyroxene nor any definite evidence that pyroxene was ever present. There are scattered small patches of fine-grained mica, chlorite, carbonate, and opaque minerals in the rock. Much of the feldspar contains small oriented rodlike inclusions, possibly rutile.

8. This rock would be classified as a soda diorite by the classification system of Shand[2] rather than an anorthosite because the feldspar is not quite calcic enough to classify the rock as anorthosite by Shand's definition. He notes that soda diorite in his classification includes the more sodic anorthosites.

9. The core log identifies the rock as noritic anorthosite and indicates that fuchsite, a green chrome mica, is present. Portions of the log for material not sent to this laboratory indicate the presence of pyroxene crystals up to 2 in. in size. The term noritic indicates pyroxene; there was no detectable pyroxene in the sample examined. We did not attempt to confirm the presence of fuchsite, but much of the green color in the rock is accounted for by chlorite.

10. The petrographic data in this report refer only to the 2-3/4-in. length of core which was examined. A quick visual inspection of the 19 ft of core received indicated that it was homogeneous. However, there is no assurance that the material examined is typical of all the core, especially if 2-in. pyroxene crystals are actually present in some of the core.

Conclusions

11. Sample A, apparently representative of the whole core, yielded a slightly lower compressive strength on the one specimen tested, but the difference is not significant. The rock was identified as soda diorite.

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[2] S. J. Shand, Eruptive Rocks, 3d edition, John Wiley & Sons, New York, N. Y., 1947.

Photograph 1. Polished surface of 2-3/4-in. length of WYO-1 DC-1(A). Magnification, X2.

Results

Schmidt number, specific gravity, porosity

12. Three samples were selected for the basic identification tests, relative hardness, specific gravity, and porosity. Results are given below:

Core	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity
8a	48.9	2.46	2.715	0.0
8b	50.3	2.70	2.715	0.0
9	51.1	2.83	2.728	0.0
Avg	50.1	2.66	2.720	0.0
Marble[3]	--	--	2.87	0.6
Granite[3]	--	--	2.66	0.9
Sandstone[3]	--	--	2.06	16.0

Examination of the data reported by Obert[3] reveals that the Laramie core is roughly comparable to a typical granite.

13. An extensive study of rock properties and tests by Deere and Miller[4] indicated a good correlation could be obtained between the compressive strength and the Schmidt number when the unit weight (specific gravity) was taken into consideration. The above data, plotted in fig. 1 as a circled dot, agree quite well with the aforementioned work.

Tensile and shear tests

14. Tensile tests were conducted by the indirect, or tensile splitting, method. Two series of single plane shear tests were conducted, one utilizing the standard NX size shear blocks (2.38 in. in diameter) and one utilizing smaller blocks (2.12 in. in diameter) fabricated for the small core (1.84 in. in diameter). Results are given below:

---

[3] Obert, Leonard, and Duvall, W. I., Rock Mechanics and the Design of Structures in Rock, 1st editio John Wiley & Sons, New York, N. Y., 1967.

[4] Deere, D. U., and Miller, R. P., "Engineering Classification and Index Properties for Intact Rock," Technical Report No. AFWL-TR-65-116, University of Illinois, Dec 1966.

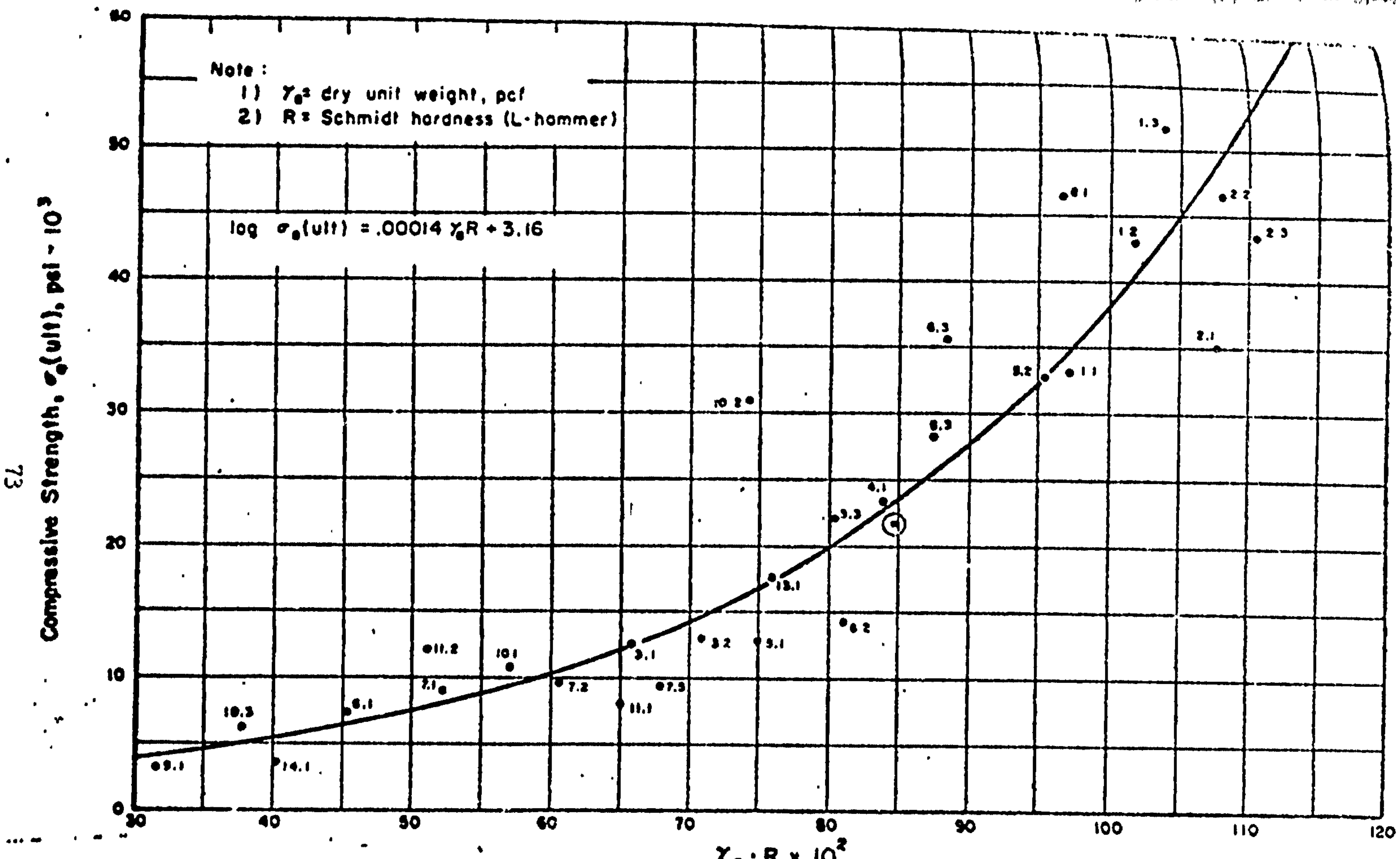


FIG. 1 - RELATIONSHIP BETWEEN AVERAGE VALUES OF $\gamma_d \cdot$R AND ULTIMATE COMPRESSIVE STRENGTH FOR ROCK IN UNIAXIAL COMPRESSION (From Deere and Miller)

Warren Siting Area: Core No. 1 (Laramie); Sample B; Series I

Core No.	Test	Strength, psi	
3a	Tensile	1370)	
3b	Tensile	1420)	1400
3c	Tensile	1410)	
5a	Shear (2.38-in. diameter)	1770)	
5b	Shear (2.38-in. diameter)	2070)	1890
5c	Shear (2.38-in. diameter)	1830)	
4a	Shear (2.12-in. diameter)	2330)	
15a	Shear (2.12-in. diameter)	2080)	2420
15b	Shear (2.12-in. diameter)	2860)	

Examination of the tensile strength data reported by Wuerker[5] reveals that the tensile strength of the Laramie core is comparatively high due possibly to the indirect method of testing. The large blocks yielded a rather low shear strength, indicating other stresses, probably including flexural, affected the results. Even the small shear blocks yielded shear strengths somewhat lower than the strength determined in the triaxial test (2420 versus 3100 psi). Posttest photographs of tensile and shear specimens are given in plates 2 and 3.

Unconfined compressive tests

15. Three conventional unconfined and one cyclic unconfined compressive tests were conducted. All specimens had two vertical and two horizontal electrical resistance strain gages affixed in order to measure strain during testing. Stress-strain curves for the conventional tests are given in plates 4, 5, and 6. The average strength was 21,700 psi for the conventional tests.

16. The cycled specimen was unloaded at 5000 psi intervals, but no hysteresis was detected until unloading at 20,000 psi (plate 7). The small amount of hysteresis indicates that the Laramie rock is a comparatively "stiff" material.

17. The average strength for the three cyclic tests, one each from samples A, B, and C, was 21,500 psi. The average strength, standard deviation, and coefficient of variation for all unconfined compressive tests were 21,580 psi, 490 psi, and 2.3 percent, respectively. Statistically, the variability is extremely small for a material such as rock.[3] One specimen, No. 7a, experienced a premature slippage along a healed fracture.

---

[5] Wuerker, R. G., "The Shear Strength of Rocks," Mining Engineering, vol 11, Oct 1959.

Although the fracture had little apparent effect on the results of this particular specimen, such fractures could affect strength and deformation properties on subsequent tests. Posttest photographs of the compressive test specimens, plate 8, show evidence of vertical splitting, often prevalent in compressive tests of brittle material.

Moduli of Deformation

18. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on three samples by the dynamic[3] (fundamental frequency) method and on the six unconfined compressive strength specimens statically using theory of elasticity. Results are given below:

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity) psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
10	11.91	4.90	7.09	0.22
12	11.56	4.54	8.38	0.27
14	12.04	4.70	9.12	0.28
		Statically		
7a	11.75	4.56	9.18	0.24
7b	11.71	4.32	9.28	0.30
7c	11.12	4.43	7.63	0.26
10a	12.50	4.88	9.52	0.25
17a*	9.00	3.52	4.64	0.28
20a**	11.58	4.55	8.52	0.25
Avg	11.77	4.51	8.59	0.26

* From sample A; deleted from average.
** From sample C.

A cursory examination of the results reveals that correlation between the two methods is good. Therefore, the average values given may be considered representative for the deformation properties of the core.

Velocity measurements

19. Compressive and shear velocities were measured on three specimens of sample B as indicated below:

Warren Siting Area: Core No. 1 (Laramie); Sample B; Series I

Core No.	Compressional Pulse Velocity, fps	Shear Velocity, fps
10	19,765	11,485
12	19,500	11,095
14	20,100	11,235
Avg	19,790	11,270

The compressional velocity was determined directly as the sonic propagation velocity, and the shear velocity was determined from the torsional frequency obtained in the moduli determinations. The shear velocity is approximately 57 percent of the compressional velocity, which is a reasonable percentage for most rocklike materials.

Warren Siting Area: Core No. 1 (Laramie); Sample C; Series I

Results

20. Only one test, a compressive strength test, was conducted on sample C. The specimen, from a depth of 153 ft, had a compressive strength of 22,300 psi. The stress-strain curve is given in plate 9.

Conclusions

21. The compressive strength is approximately equal to the strength of specimens at the other depths; therefore, the rock apparently is rather homogeneous throughout the interval tested.

Warren Siting Area: Core No. 1 (Laramie); Sample B; Series II

Results

Hydrostatic compression

22. Hydrostatic compressive tests were conducted on three specimens, one each to pressures of 8000, 20,000, and 36,000 psi. The specimens were prepared in a manner similar to the unconfined compressive tests except that 1/2-in. foil gages affixed with epoxy were utilized rather than wire gages. Tests on a steel specimen and literature[6] indicated negligible effects of confining pressure on foil strain gages. Stress-strain curves for the horizontal and vertical deformations for the three tests are given in plates 10-15. Utilizing the results of the best three loading cycles, the bulk modulus, K, was computed from the relation:

$$K = \frac{\sigma}{\epsilon_1 + \epsilon_2 + \epsilon_3}$$

where:

σ = hydrostatic stress

ϵ_1 = vertical strain

$\epsilon_2 = \epsilon_3$ = horizontal strain

Specimen No.	Maximum Stress, psi	Bulk Modulus, K, psi
14d	8,000	11.19
14a	20,000	8.39
2a	36,000	9.77

The bulk moduli agree quite well with the dynamically determined moduli except for specimen No. 14d. The unusually high result may be due to testing error. The erratic behavior of the horizontal gages on specimen 14a during the first loading cycle is believed to be due to seating of the gages rather than actual deformation of the specimen.

Triaxial compression

23. Triaxial tests were conducted on the same specimens utilized for the hydrostatic tests at confining pressures equal to the hydrostatic pressures previously applied. Stress-strain curves are given in plates 16, 17, and 18. Young's modulus, computed as the initial tangent, and Poisson's ratio are given below:

---

[6] Milligan, R. V., "The Effects of High Pressure on Foil Strain Gages," Experimental Mechanics, 4 (2), 25-36, 1964.

Warren Siting Area: Core No. 1 (Laramie); Sample B; Series II

Specimen No.	σ_3, psi	E, psi x 10^6	Poisson's Ratio
14d	8,000	13.5	0.33
14a	20,000	11.0	0.31
2a	36,000	12.0	0.29

The results are not significantly different from those obtained in the unconfined compressive tests.

24. The Mohr's circles for the lower stress range, given in plate 19, indicate an unconfined shear strength of approximately 3100 psi. The circles for all tests are given in plate 20. The envelope is apparently straight line up to the 20,000 psi confining pressure level at an angle of 41.5 deg and then assumes a curvilinear relationship with increased confining pressure; however, pronounced shear planes developed in the specimen tested at 8000 and 20,000 psi confining pressure, and initial failure occurred along a crystal face in the 36,000 psi test specimen. Thus, the curvature of the envelope may be due to premature yielding along the crystal interface. Pre- and posttest dimensions for the 20,000 and 36,000 psi tests are given in plates 21 and 22, respectively. Posttest photographs are given in plate 23.

25. The compressional wave velocity was recorded during test to failure of two specimens, 2a and 14d. The results in plates 15 and 17 indicate that the velocity increases initially under load probably due to closure of small cracks and then remains rather constant up to failure.

Confined compression

26. Confined compression tests were conducted on two specimens prepared essentially as the triaxial test specimens. Confining pressure was applied to prevent lateral straining as axial load was applied by the piston. Therefore, a pseudo one-dimensional state of stress was induced, from which can be computed a constrained modulus. The axial stress-strain curves are given in plates 24 and 25. The lateral stress required to maintain a condition of no lateral strain is given on the far left of the curves.

27. The constrained modulus, M_c, may be computed from theory of elasticity:

$$M_c = \frac{E\ (1-u)}{(1+u)\ (1-2u)}$$

where:

E = Young's modulus

u = Poisson's ratio

Warren Siting Area: Core No. 1 (Laramie); Sample B; Series II

Using the results from the triaxial tests ($E = 12.2 \times 10^6$ psi; $u = 0.31$), the constrained modulus theoretically would average 16.9×10^6 psi. The constrained moduli computed as the initial tangent to the stress-strain curves are 17.0×10^6 and 15.5×10^6 psi for specimens 1a and 14c, respectively. Good correlation is, therefore, indicated between the theoretical and experimental results.

Conclusions: Laramie Core

28. The Laramie core is a rather brittle material classified as soda diorite with an estimated 80 percent of the rock plagioclase feldspar. Consensus results of some physical properties include: compressive strength, 21,600 psi; Young's modulus, 11.8×10^6 psi; bulk modulus, 8.6×10^6 psi; specific gravity, 2.72; compressional wave velocity, 19,800 fps. The rock was very homogeneous with depth for the length sampled 17 to 150 ft. The large crystal size, estimated to be 2 in. or larger in the core log, apparently did not significantly affect the results. The variations in test properties were very small for a material such as rock. The triaxial tests indicated that the Mohr's envelope was straight line at an angle of 41.5 deg up to at least 20,000 psi confining pressure. The highest pressure available for these tests, 36,000 psi, did not allow full definition of the envelope. Little hysteresis was evident in the stress-deformation tests, indicating very little energy absorptive capacity for the intact rock.

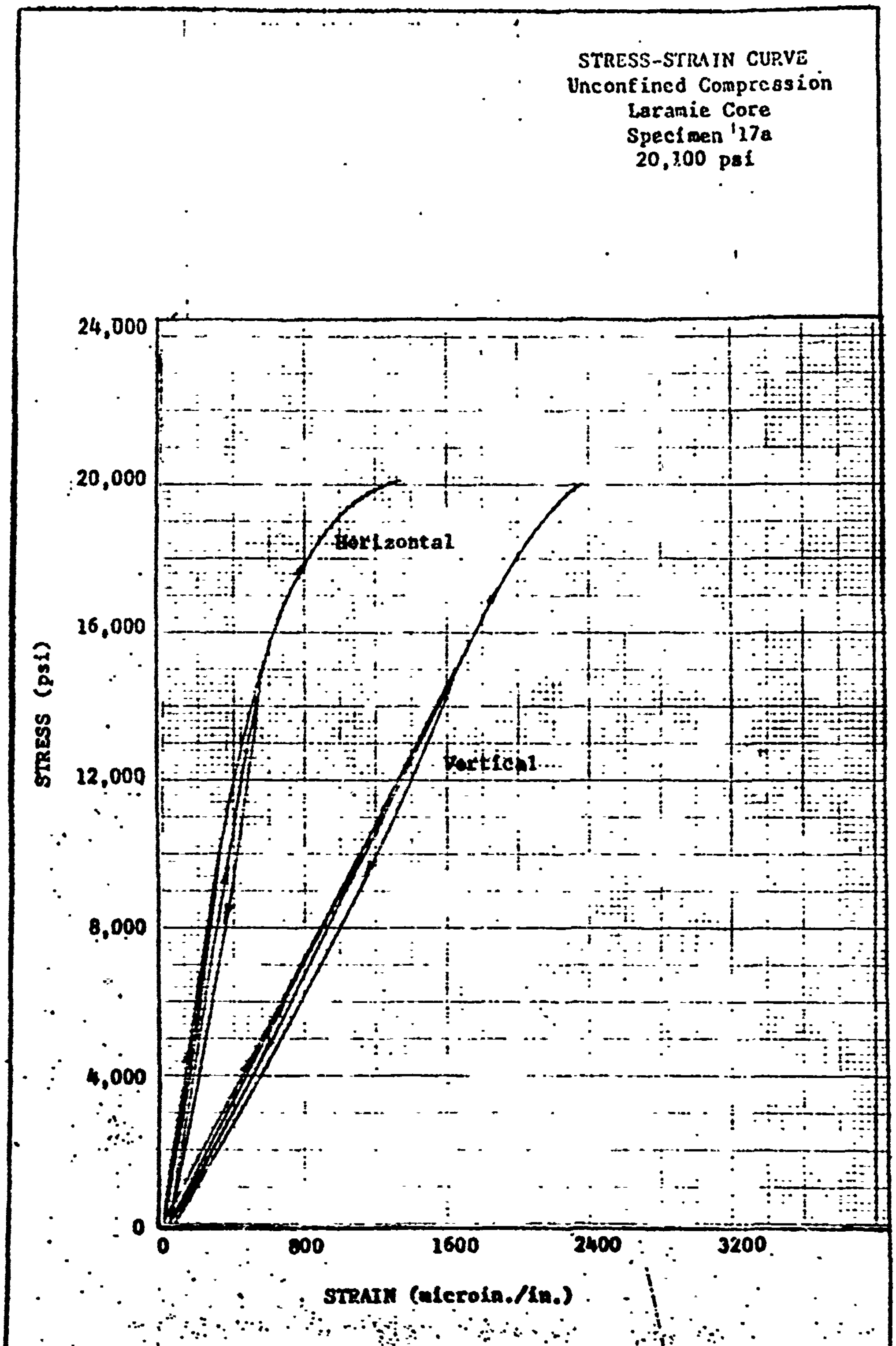
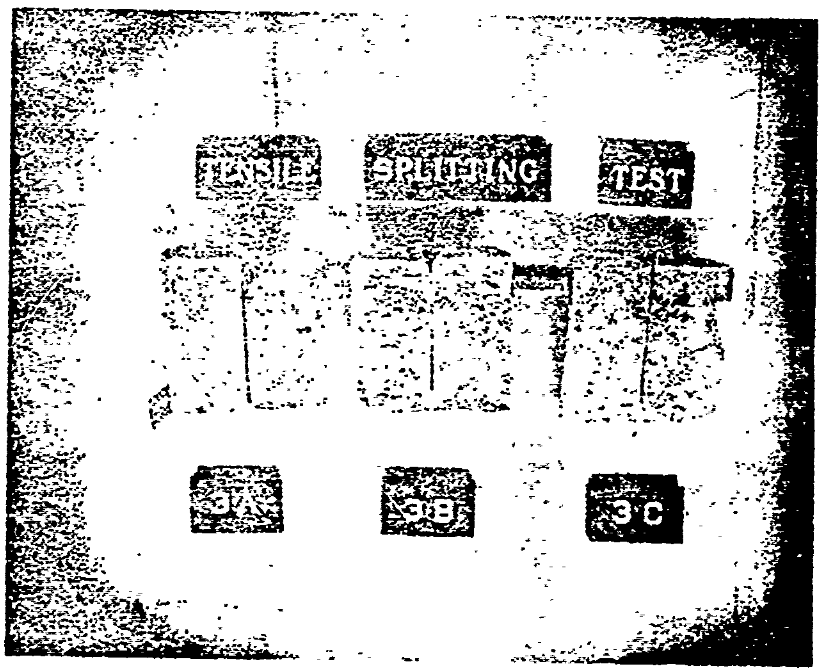
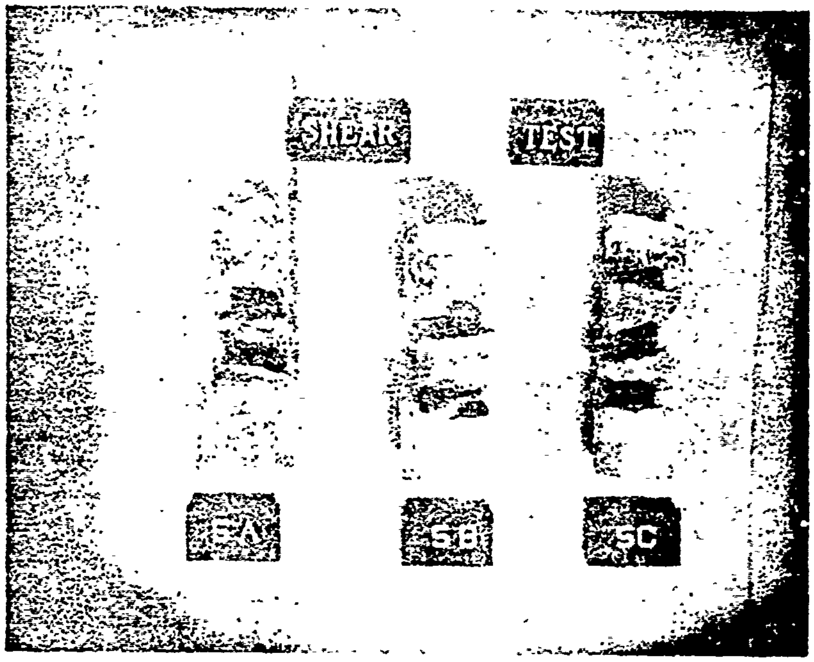
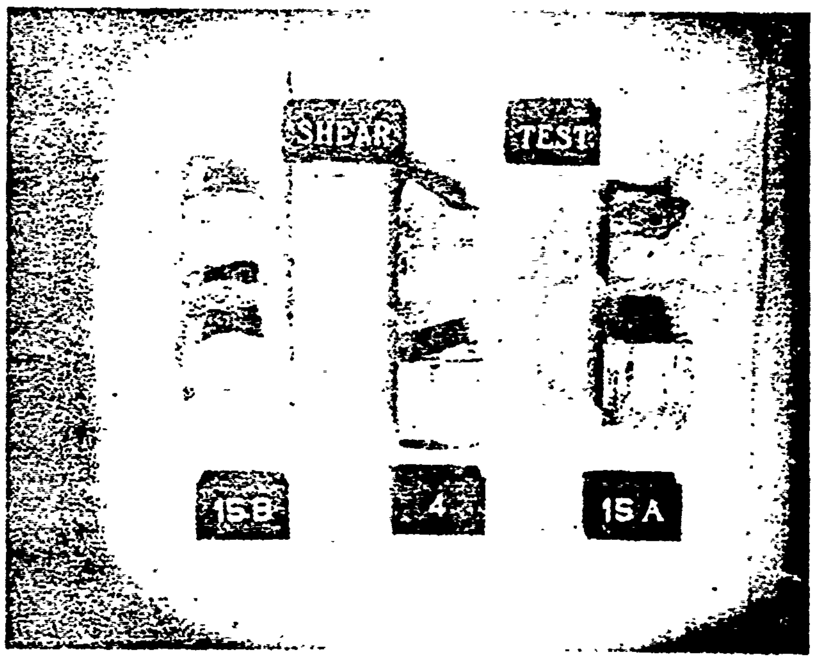

STRESS-STRAIN CURVE
Unconfined Compression
Laramie Core
Specimen '17a
20,100 psi
24,000
20,000
16,000
12,000
8,000
4,000
0
STRESS (psi)
Horizontal
Vertical
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 1



Posttest photograph





Posttest photographs

PLATE 3

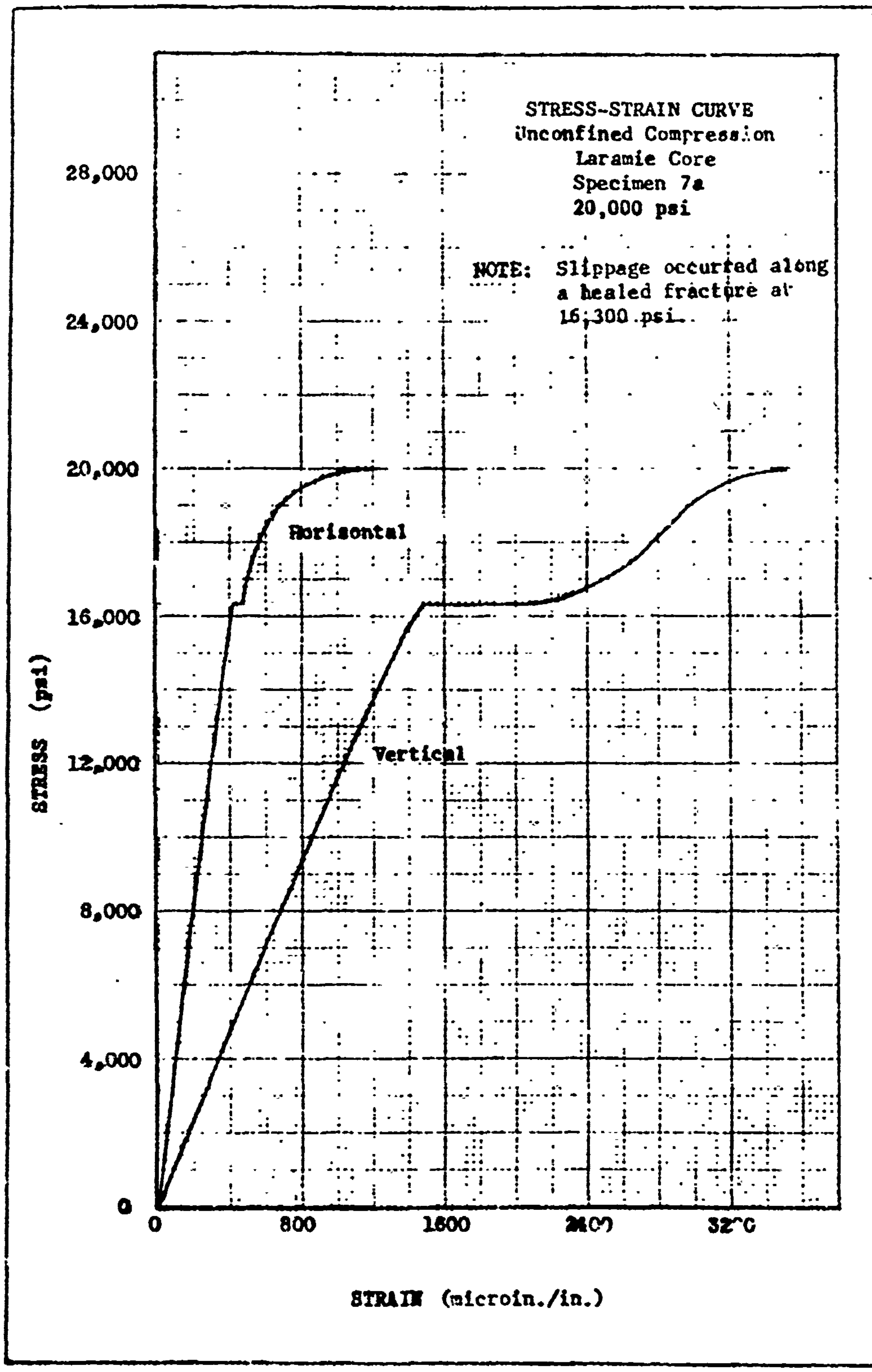

STRESS-STRAIN CURVE
Unconfined Compression
Laramie Core
Specimen 7a
20,000 psi
NOTE: Slippage occurred along a healed fracture at 16,300 psi.
Horizontal
Vertical
STRESS (psi)
28,000
24,000
20,000
16,000
12,000
8,000
4,000
0
0
800
1600
STRAIN (microin./in.)

PLATE 4

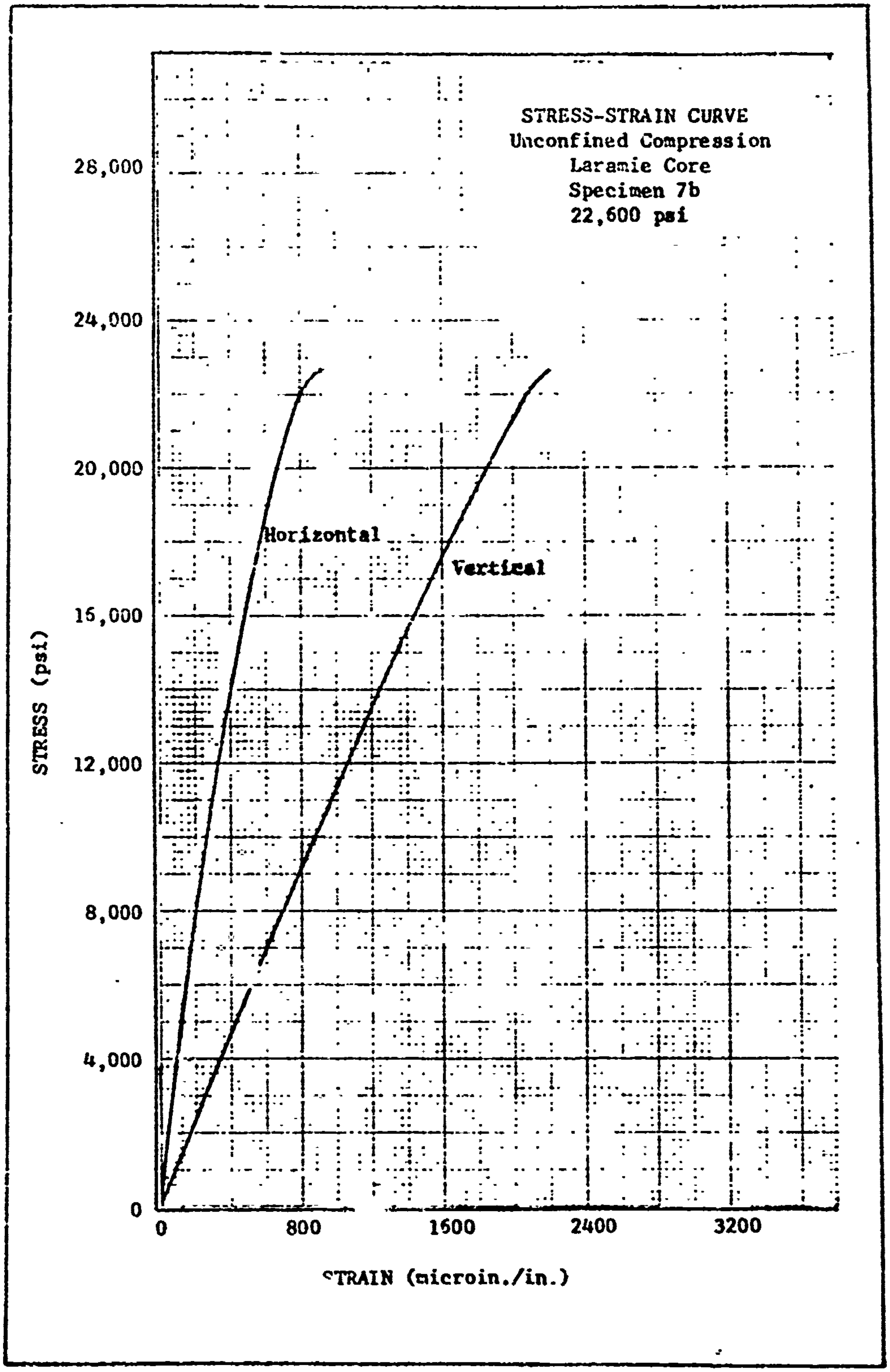

STRESS-STRAIN CURVE
Unconfined Compression
Laramie Core
Specimen 7b
22,600 psi
Horizontal
Vertical
STRESS (psi)
28,000
24,000
20,000
16,000
12,000
8,000
4,000
0
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 5

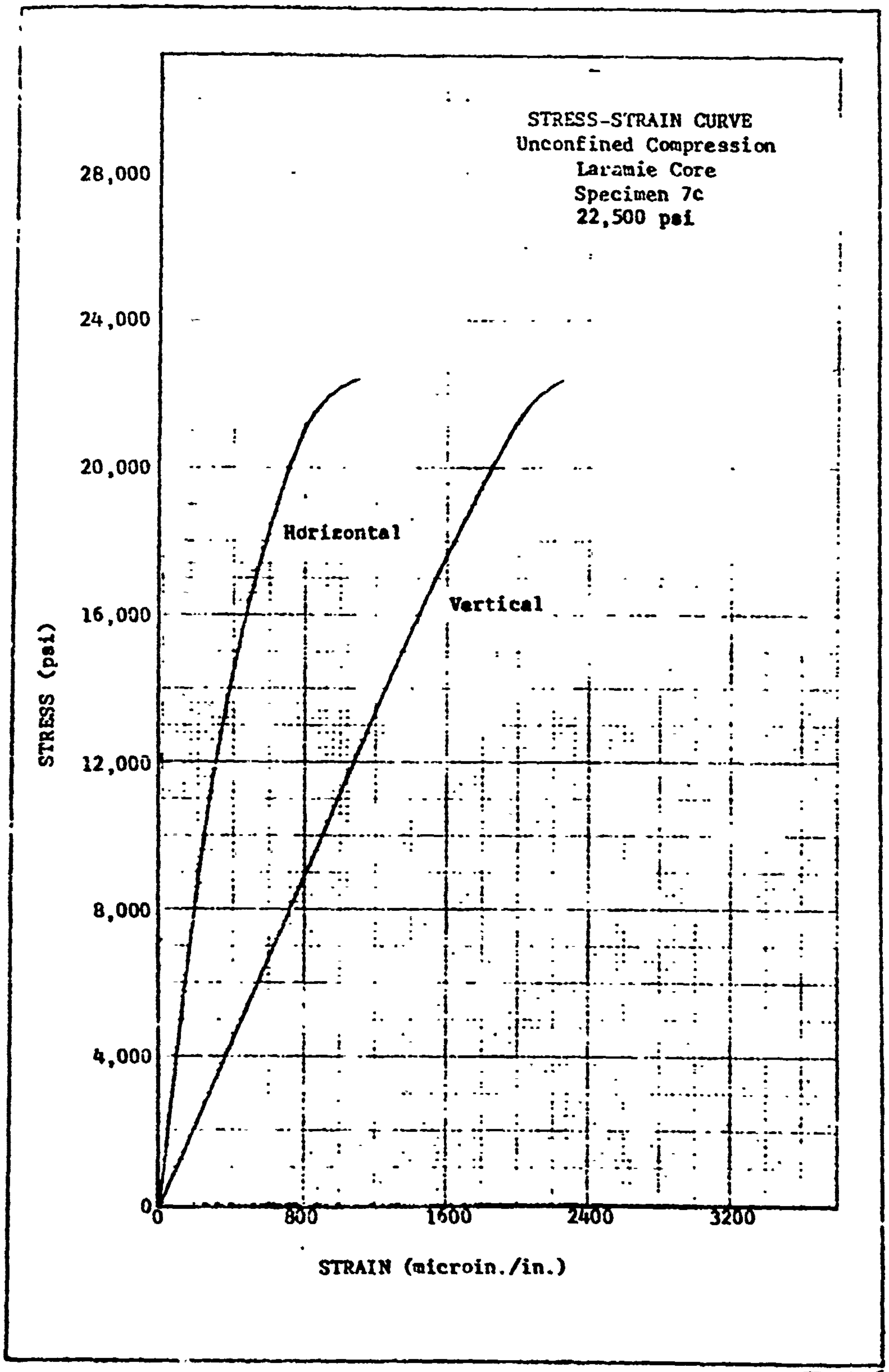

STRESS-STRAIN CURVE
Unconfined Compression
Laramie Core
Specimen 7c
22,500 psi
28,000
24,000
20,000
16,000
12,000
8,000
4,000
0
0
800
1600
2400
3200
STRESS (psi)
STRAIN (microin./in.)
Horizontal
Vertical

PLATE 6

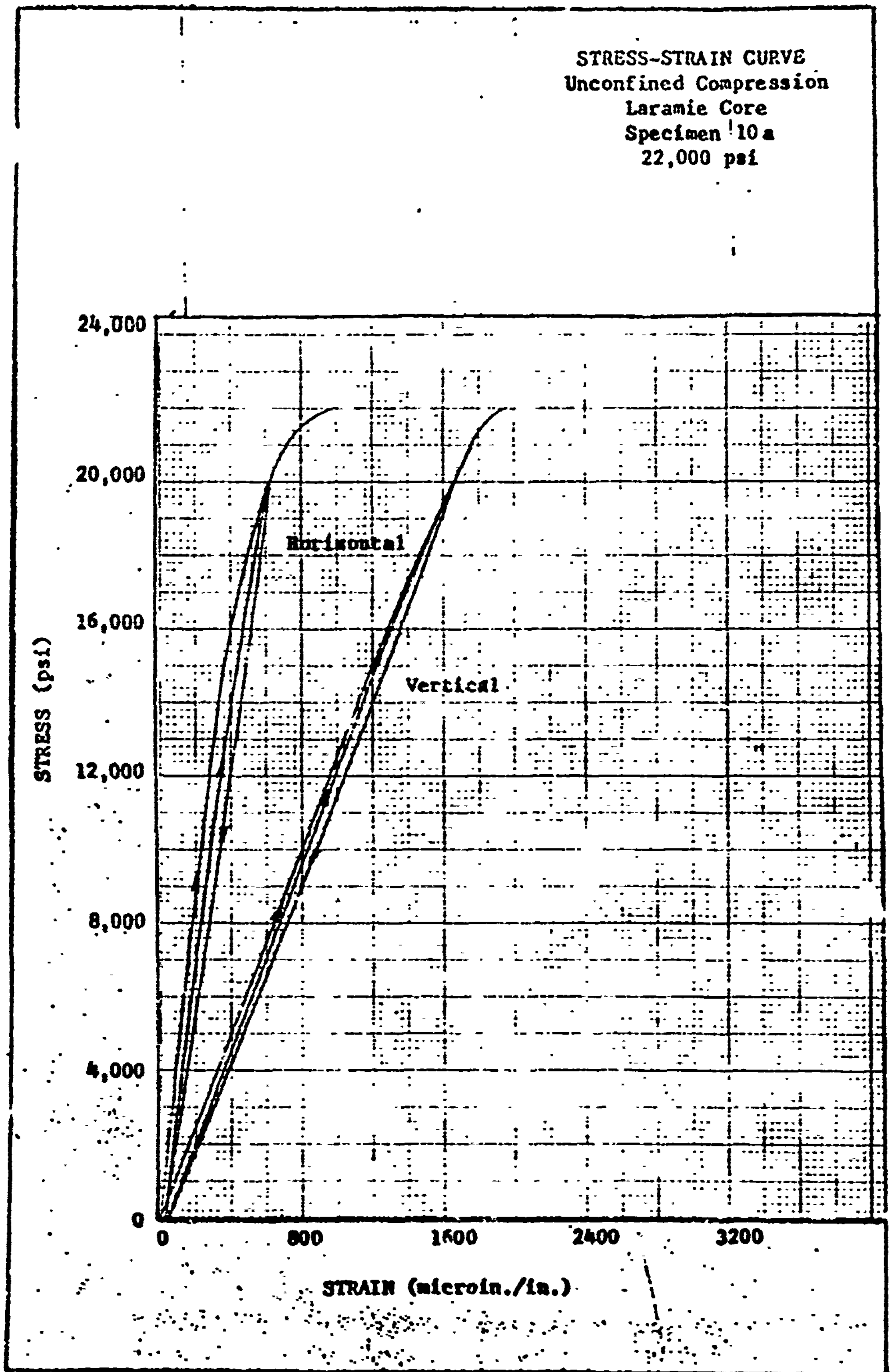
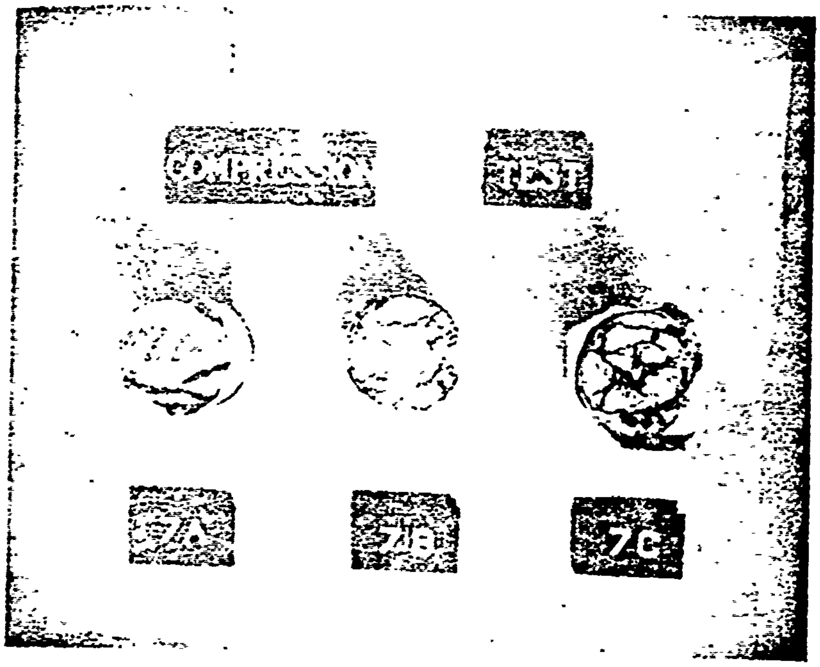
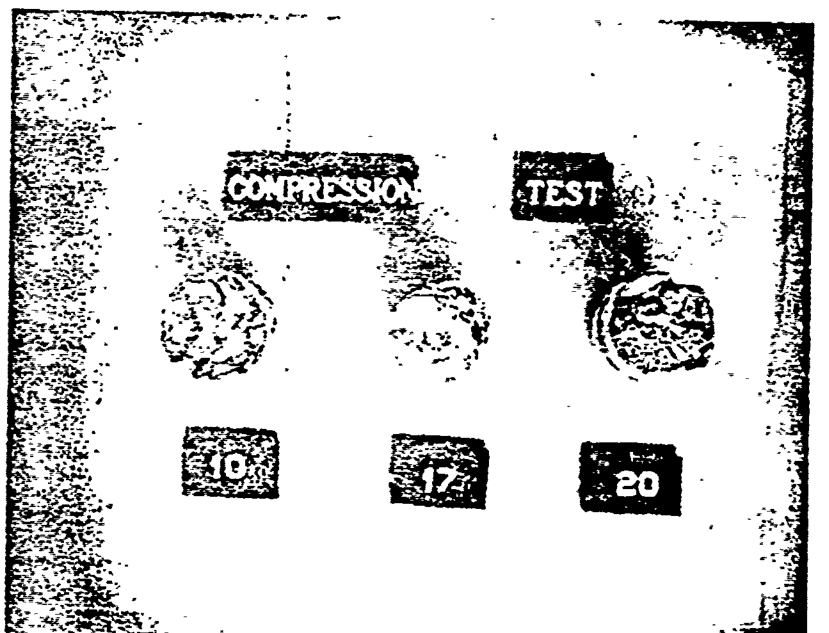

STRESS-STRAIN CURVE
Unconfined Compression
Laramie Core
Specimen 10 a
22,000 psi
Horizontal
Vertical
STRESS (psi)
24,000
20,000
16,000
12,000
8,000
4,000
0
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 7





Posttest photographs

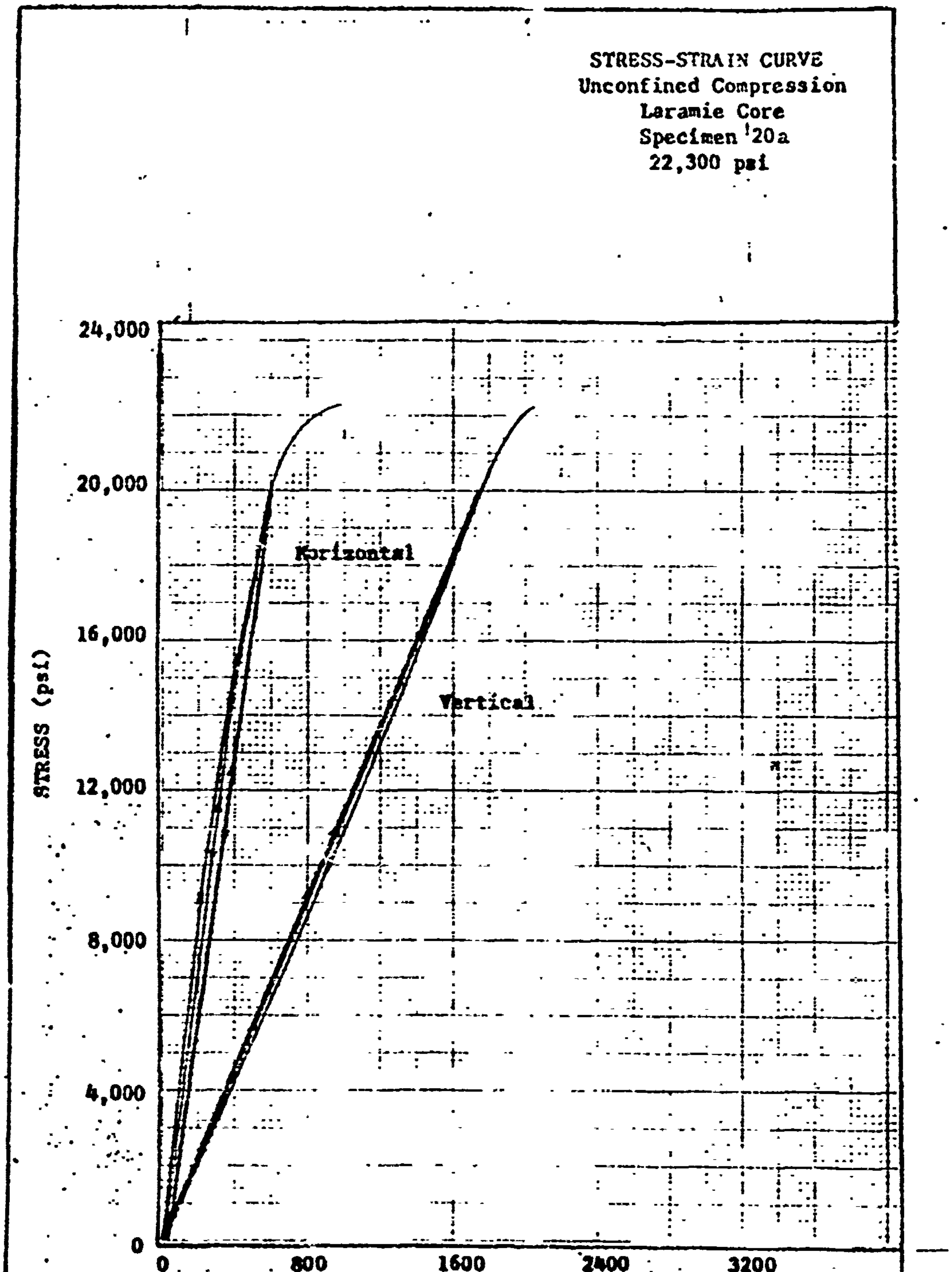

STRESS-STRAIN CURVE
Unconfined Compression
Laramie Core
Specimen 20a
22,300 psi
Horizontal
Vertical
STRESS (psi)
24,000
20,000
16,000
12,000
8,000
4,000
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 9

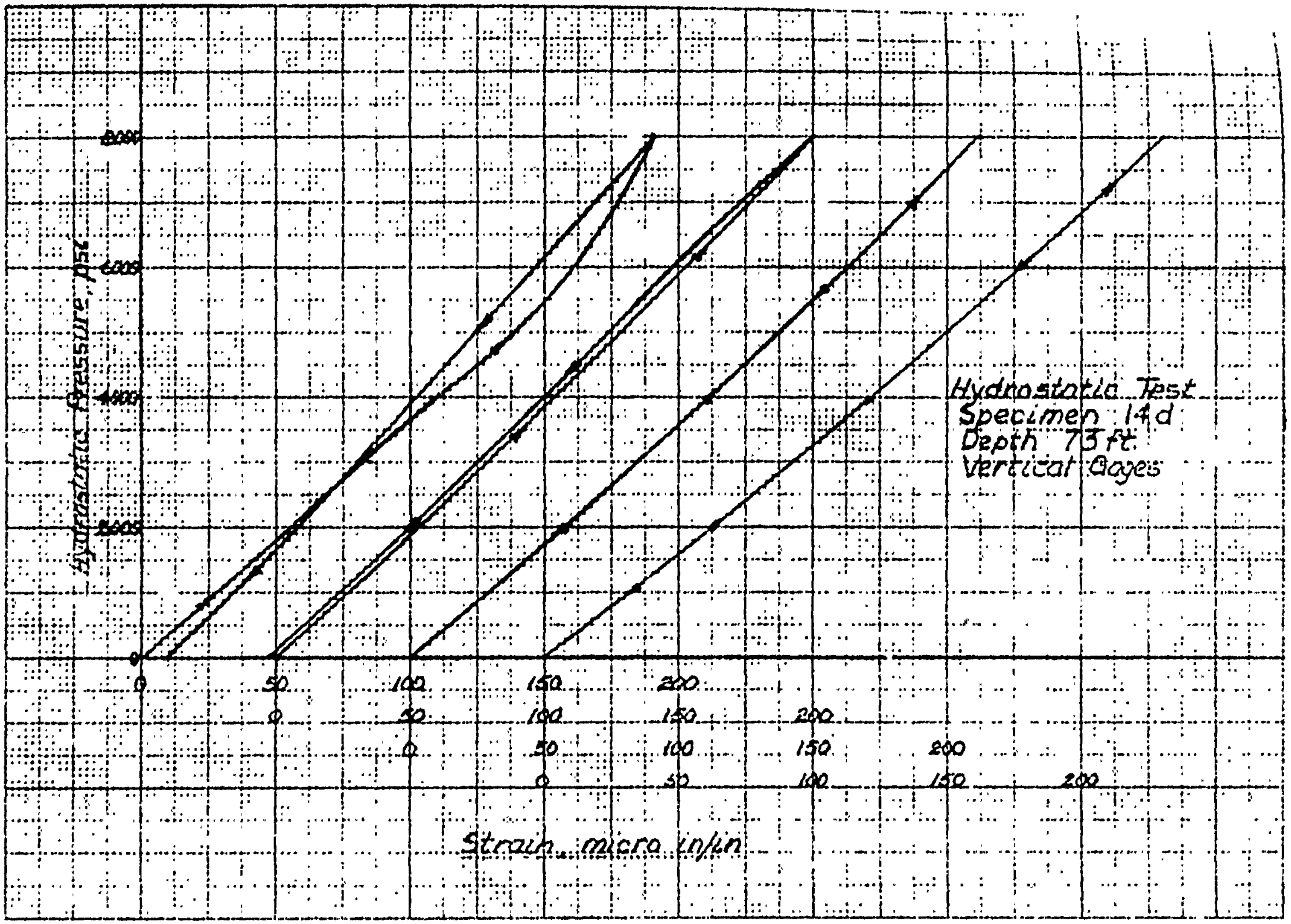
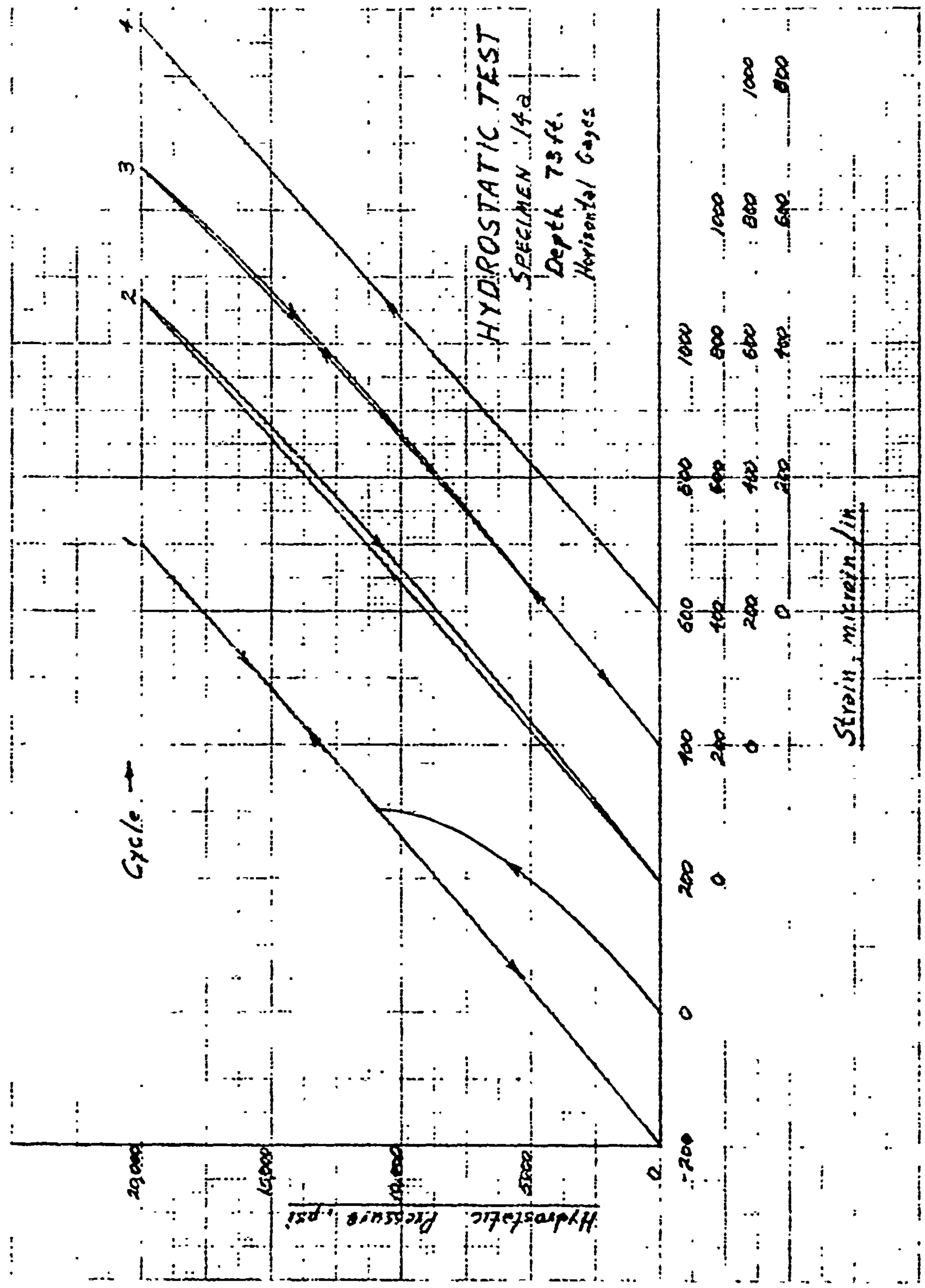
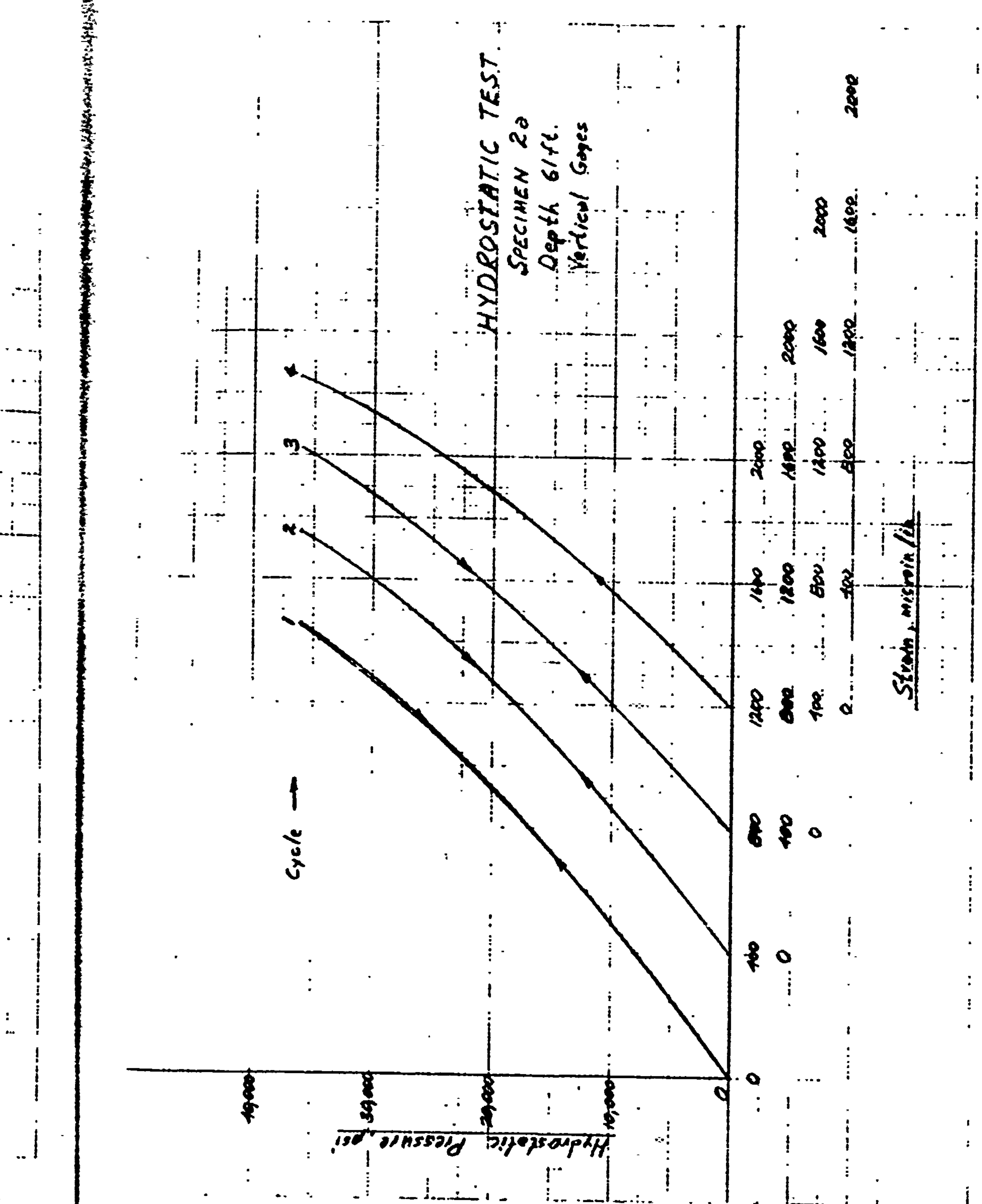

Hydrostatic Test
Specimen 14d
Depth 73 ft.
Vertical Gages
Hydrostatic Pressure, psi
8000
6000
4000
2000
0
0 50 100 150 200
0 50 100 150 200
0 50 100 150 200
0 50 100 150 200
Strain, micro in/in

PLATE 10



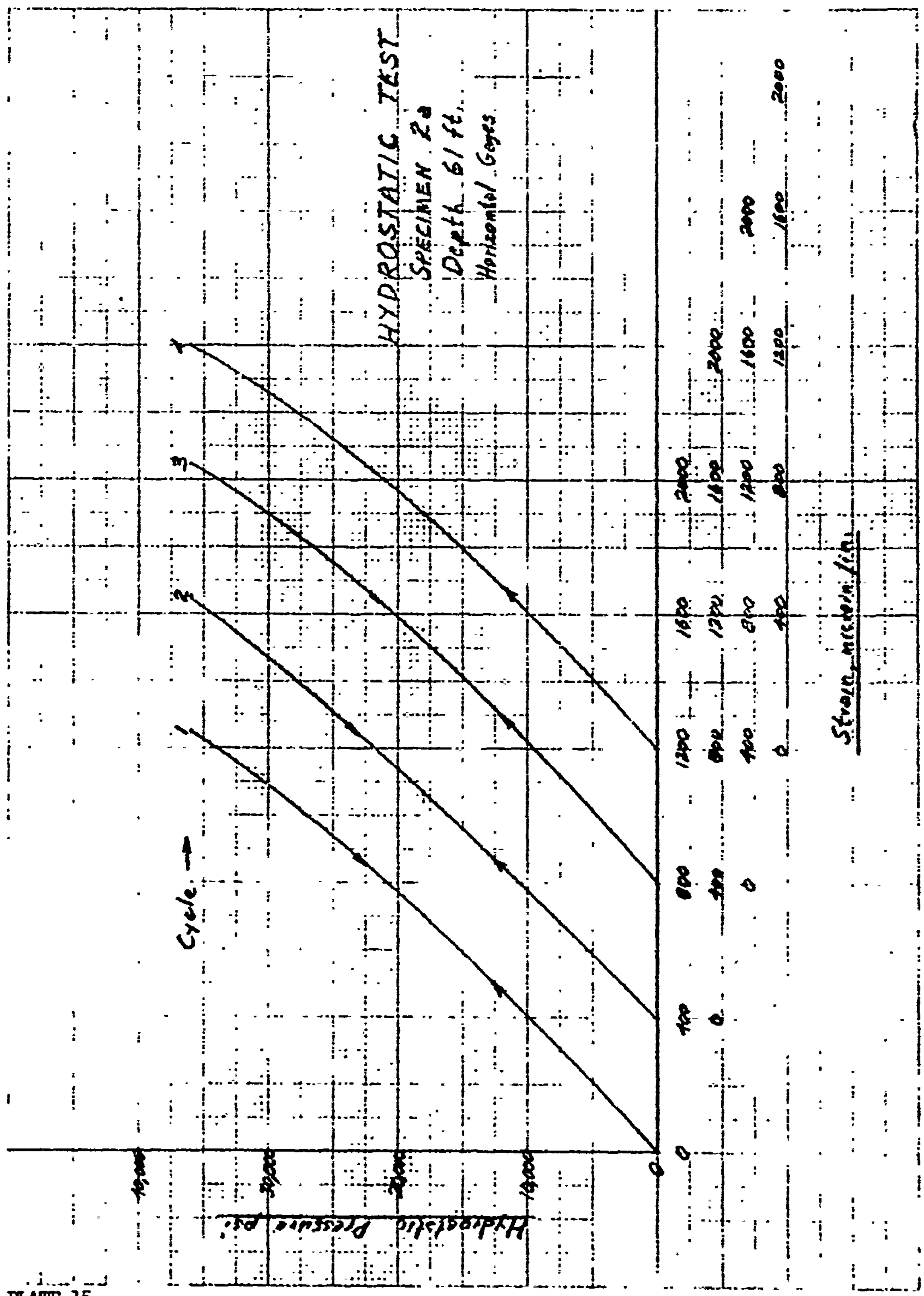
HYDROSTATIC TEST
SPECIMEN 14a
Depth 73 ft.
Horizontal Gages
Cycle →
1
2
3
4
Hydrostatic Pressure, psi
20,000
15,000
10,000
5000
0
Strain, microin./in.
-200
0
200
400
600
800
1000
0
200
400
600
800
1000
0
200
400
600
800
1000
0
200
400
600
800

PLATE 13



HYDROSTATIC TEST
Specimen 2a
Depth 61ft.
Vertical Gages
Cycle →
1
2
3
4
Hydrostatic Pressure, psi
0
10,000
20,000
30,000
40,000
Strain, microin/in

PLATE 14



HYDROSTATIC TEST
SPECIMEN 2a
Depth 61 ft.
Horizontal Gages
Cycle →
Hydrostatic Pressure psi.
Strain, micro-in./in.

PLATE 15

Strain, microin./in.

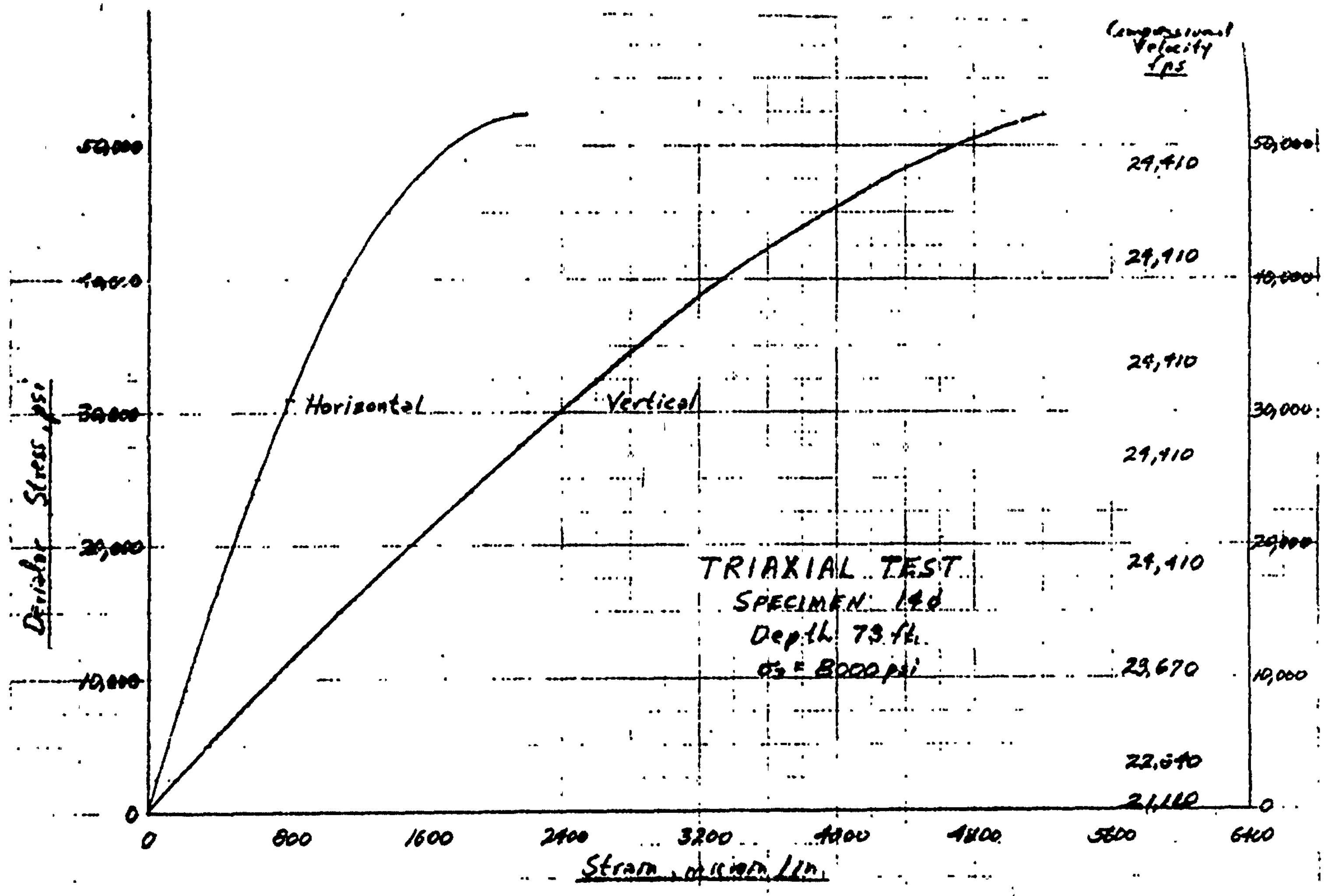


PLATE 16

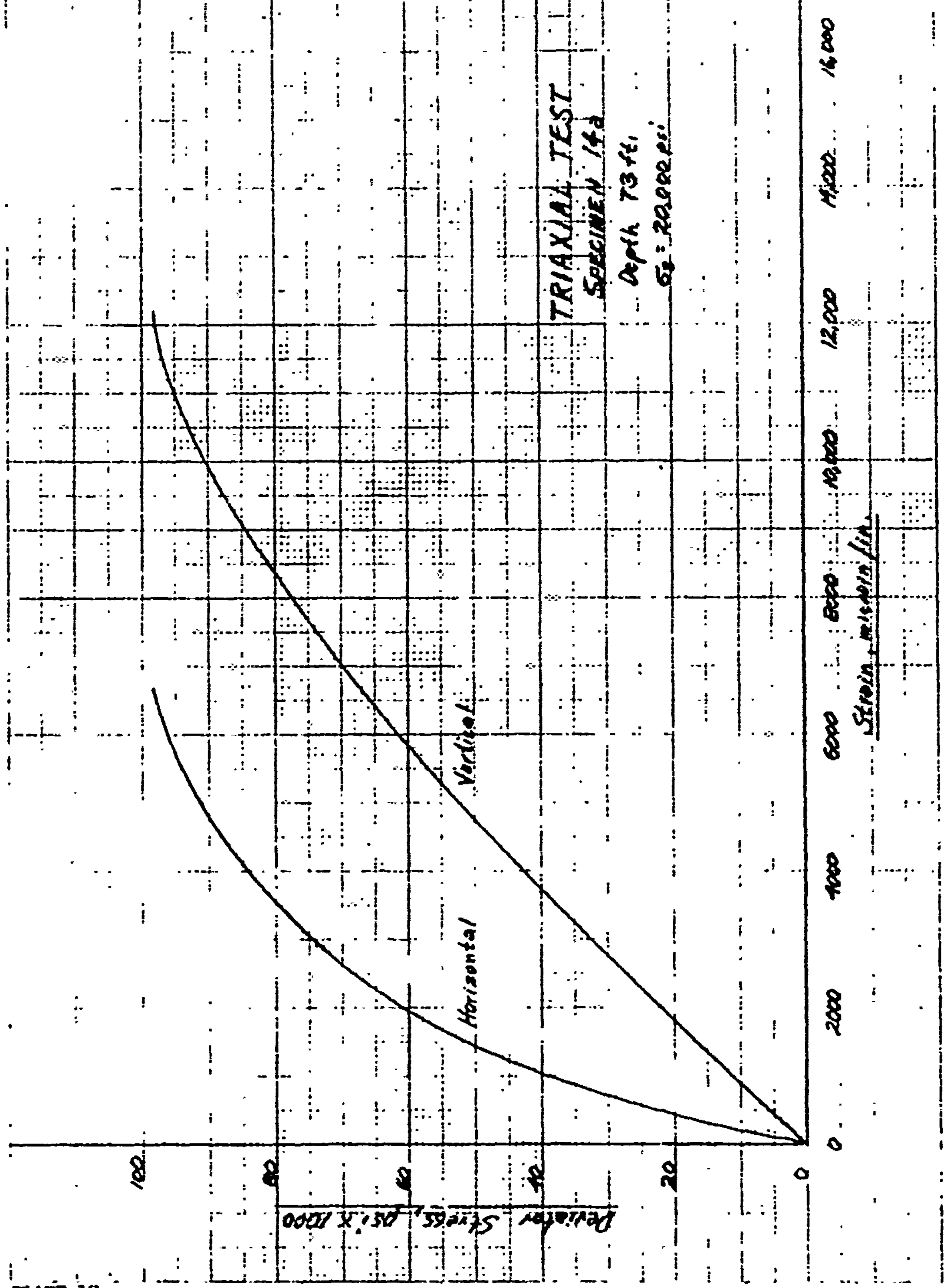
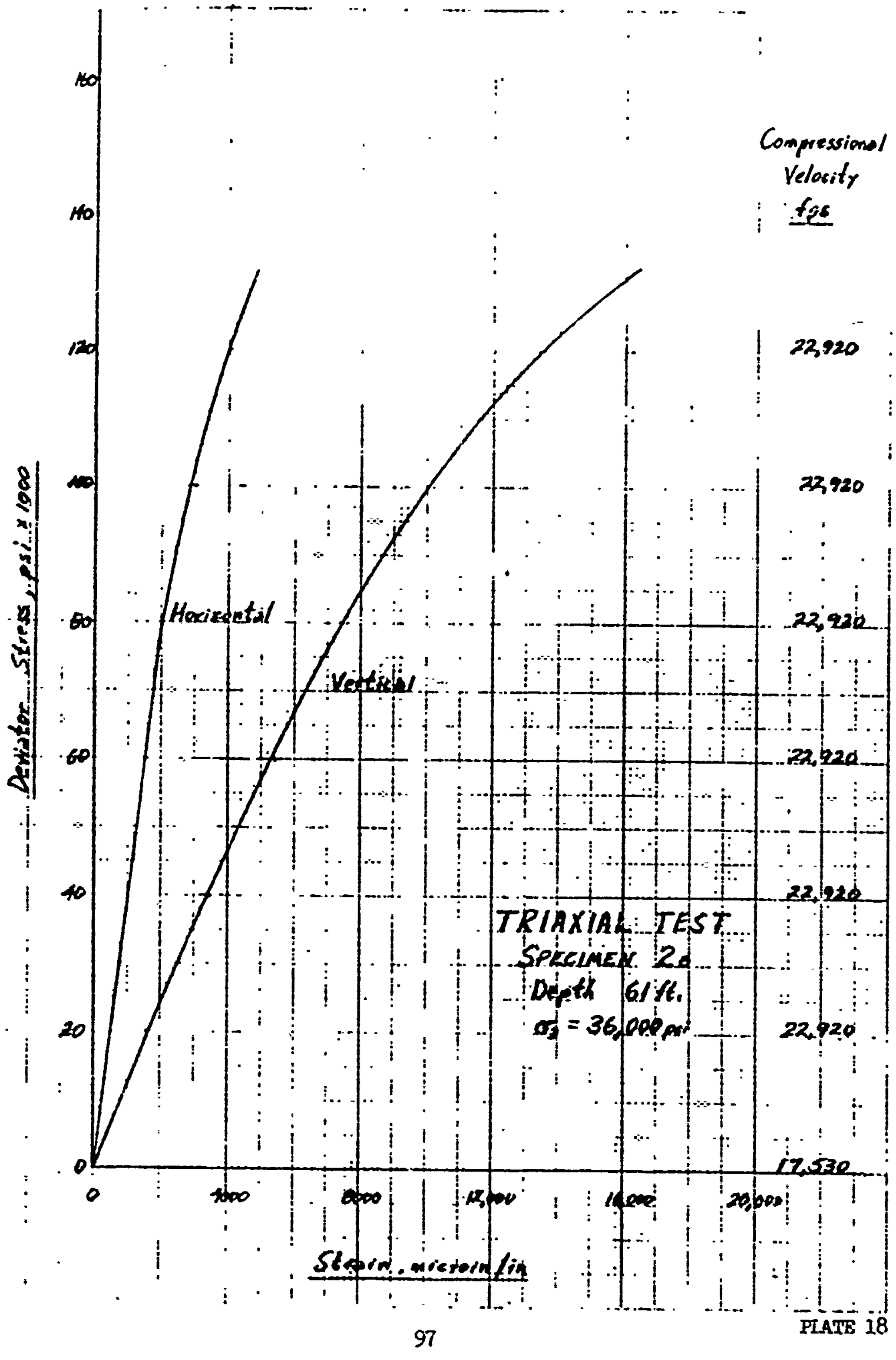

TRIAXIAL TEST
SPECIMEN 14a
Depth 73 ft.
σ3 = 20,000 psi
Vertical
Horizontal
Deviator Stress, psi x 1000
Strain, microin./in.
0
20
40
60
80
100
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000

PLATE 17



Compressional Velocity fps
22,920
22,920
22,920
22,920
22,920
22,920
17,530
Horizontal
Vertical
TRIAXIAL TEST
SPECIMEN 2a
Depth 61 ft.
σ_3 = 36,000 psi
Deviator Stress, psi x 1000
Strain, microin/in

PLATE 18

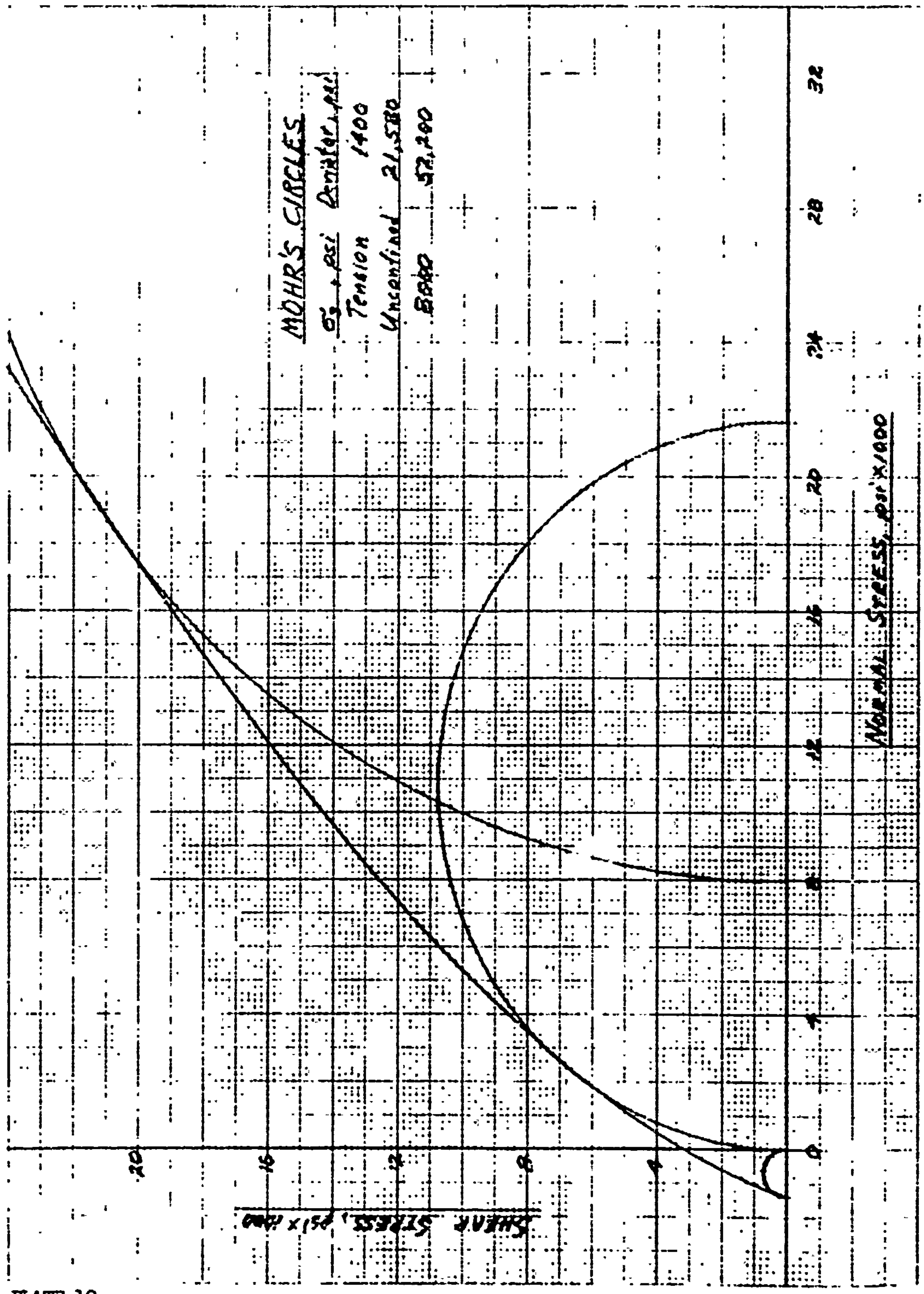
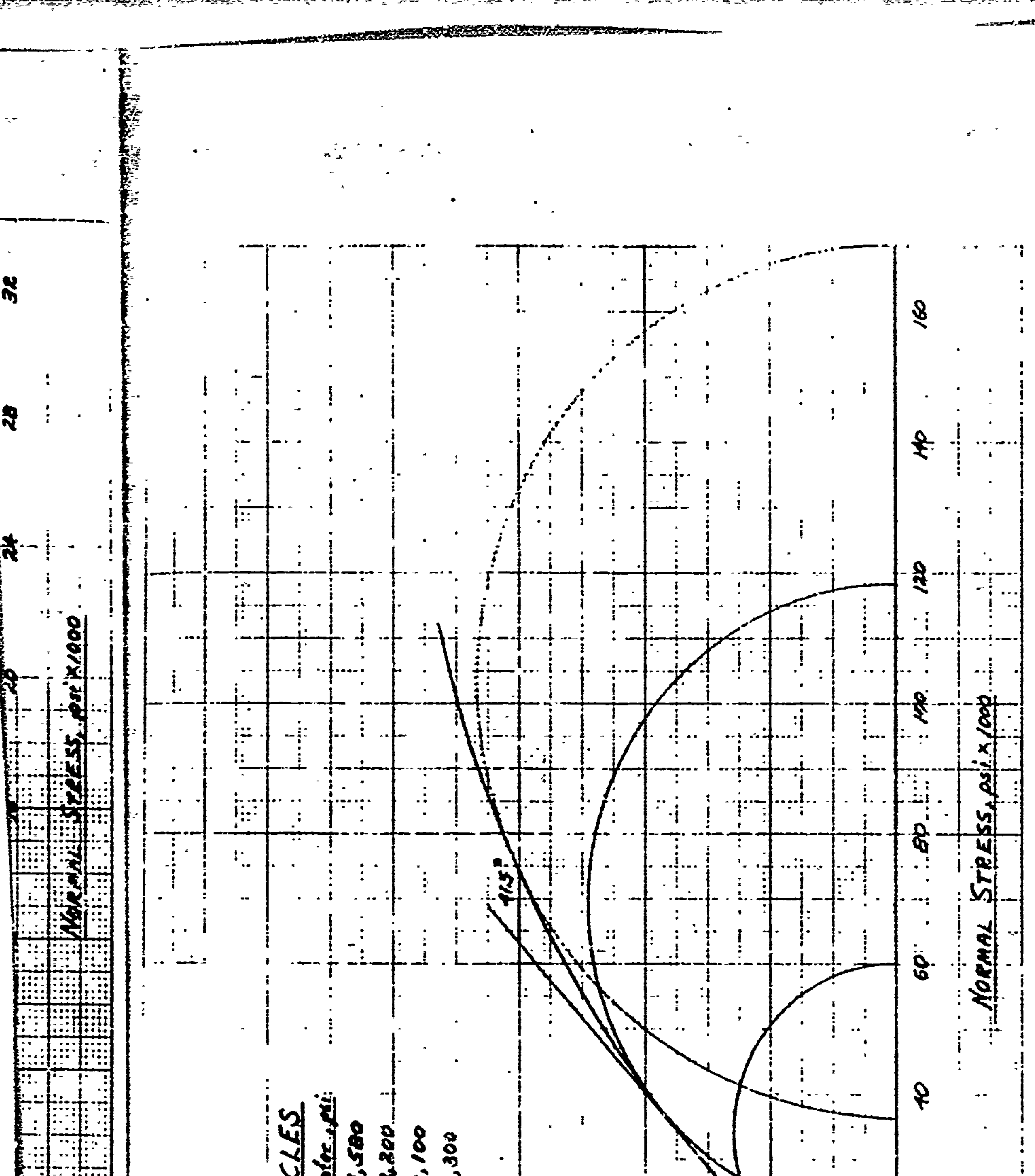

MOHR'S CIRCLES
σ_3, psi Deviator, psi
Tension 1400
Unconfined 21,580
8880 57,200
NORMAL STRESS, psi X 1000
SHEAR STRESS, psi X 1000
0
4
8
12
16
20
24
28
32

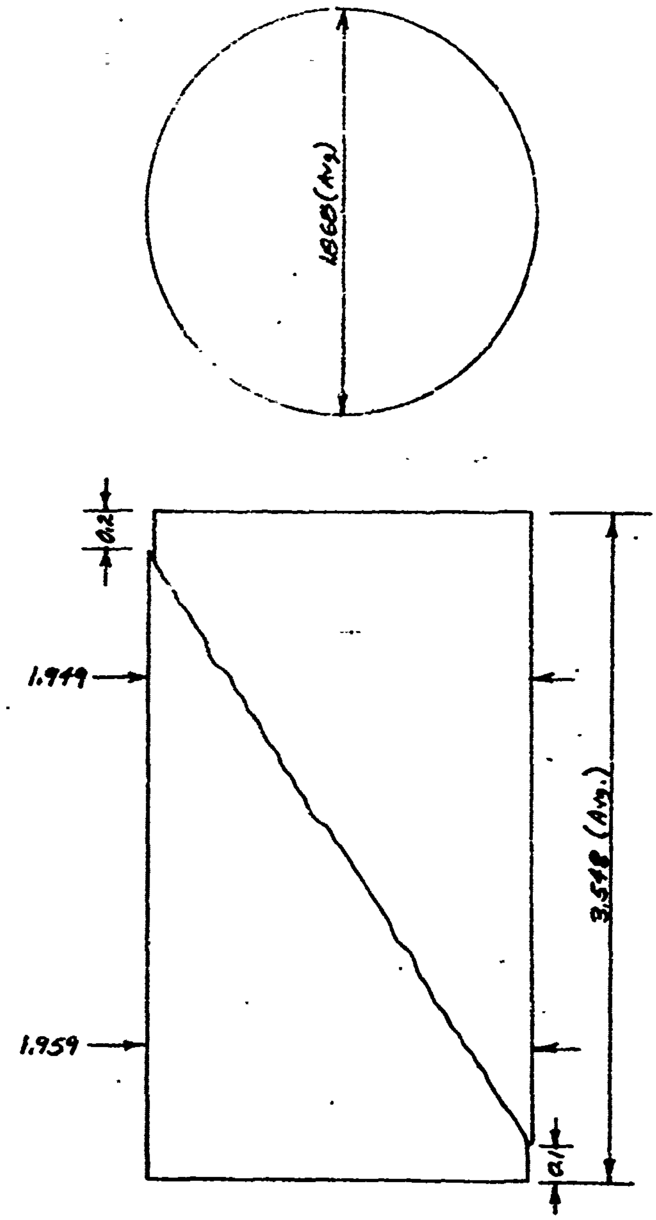
PLATE 19



MOHR'S CIRCLES
σ3, psi.	Deviator, psi.
Unconfined	21,580
8000	52,200
20,000	98,100
36,000	134,300
41.5°
NORMAL STRESS, psi x 1000
SHEAR STRESS, psi x 1000
0
20
40
60
80
100
120
140
160

PLATE 20

SUBJECT: Triaxial Test Specimen, 14a	COMPUTED BY: KLS	DATE: 7/8/58
	CHECKED BY:	DATE:

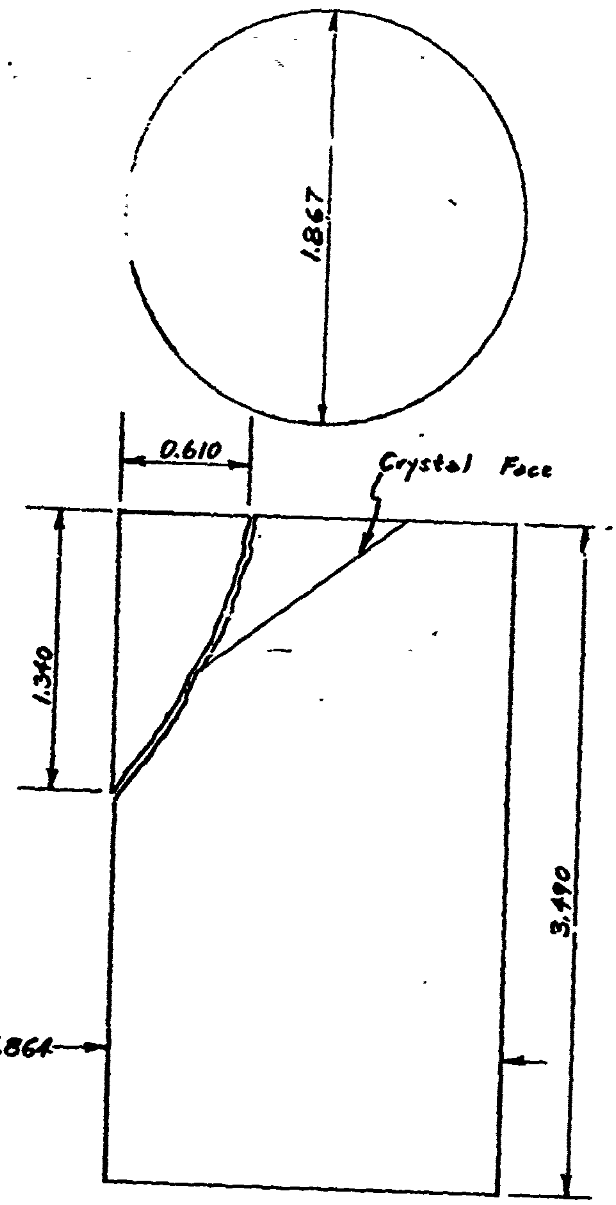


POST TEST DIMENSIONS

ORIGINAL DIMENSIONS: Diameter = 1.864 in.
Length = 3.619 in.

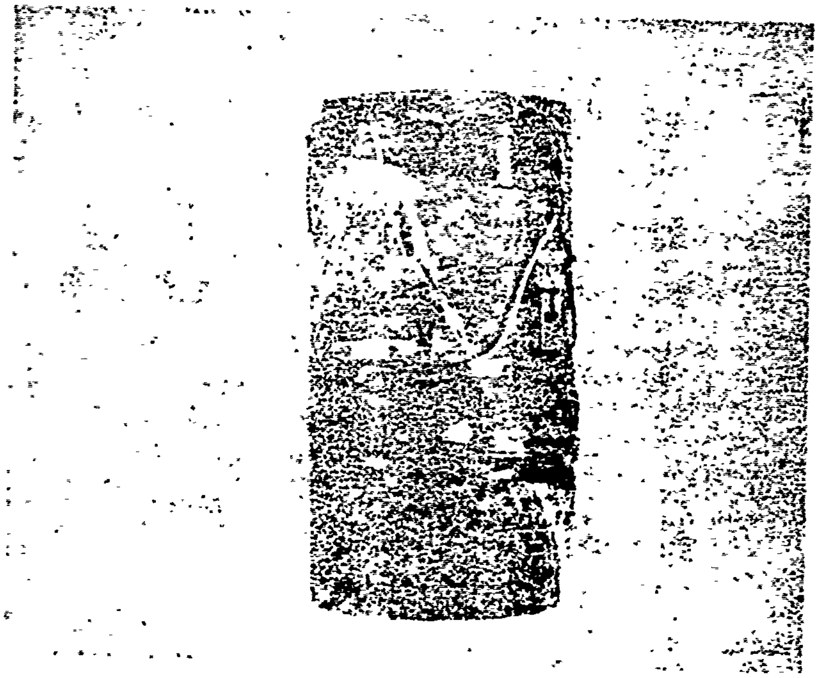
PLATE 21

Triaxial Test Specimen, 2a	COMPUTED BY: KLS	DATE: 7/18/68
	CHECKED BY:	DATE:

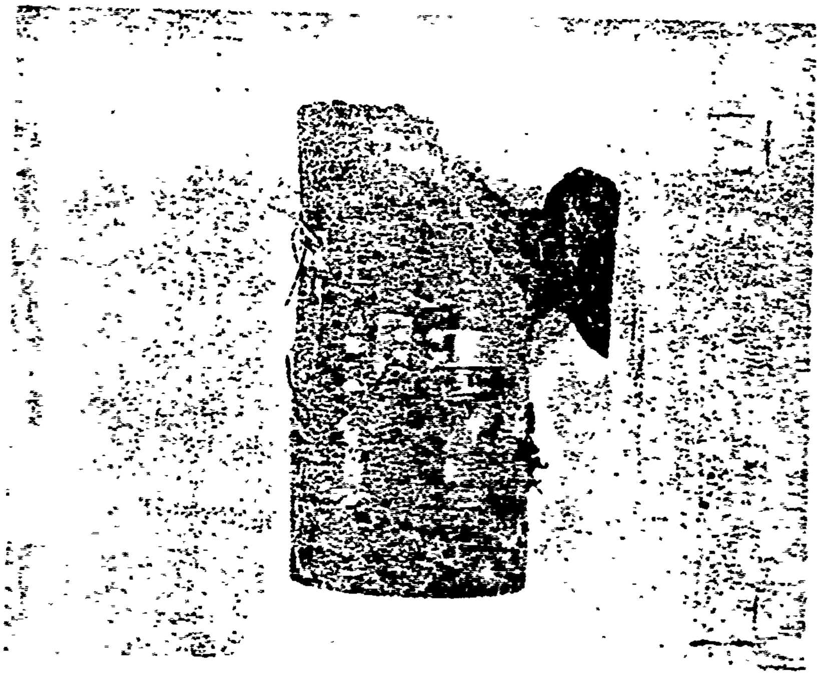


POST TEST DIMENSIONS

ORIGINAL DIMENSIONS: Diameter = 1.864 in.
Length = 3.573 in.

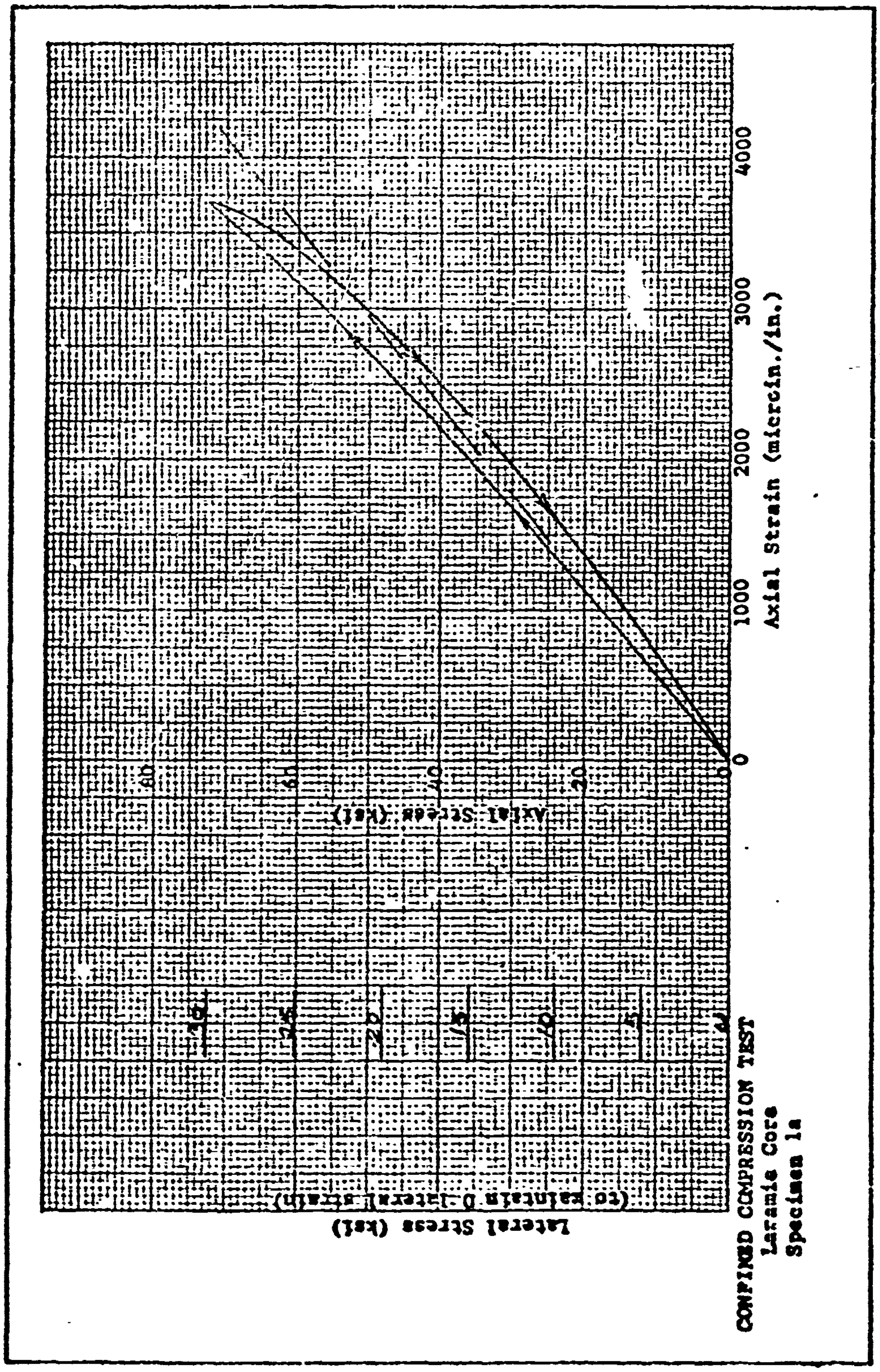


Posttest photograph triaxial specimen 14a



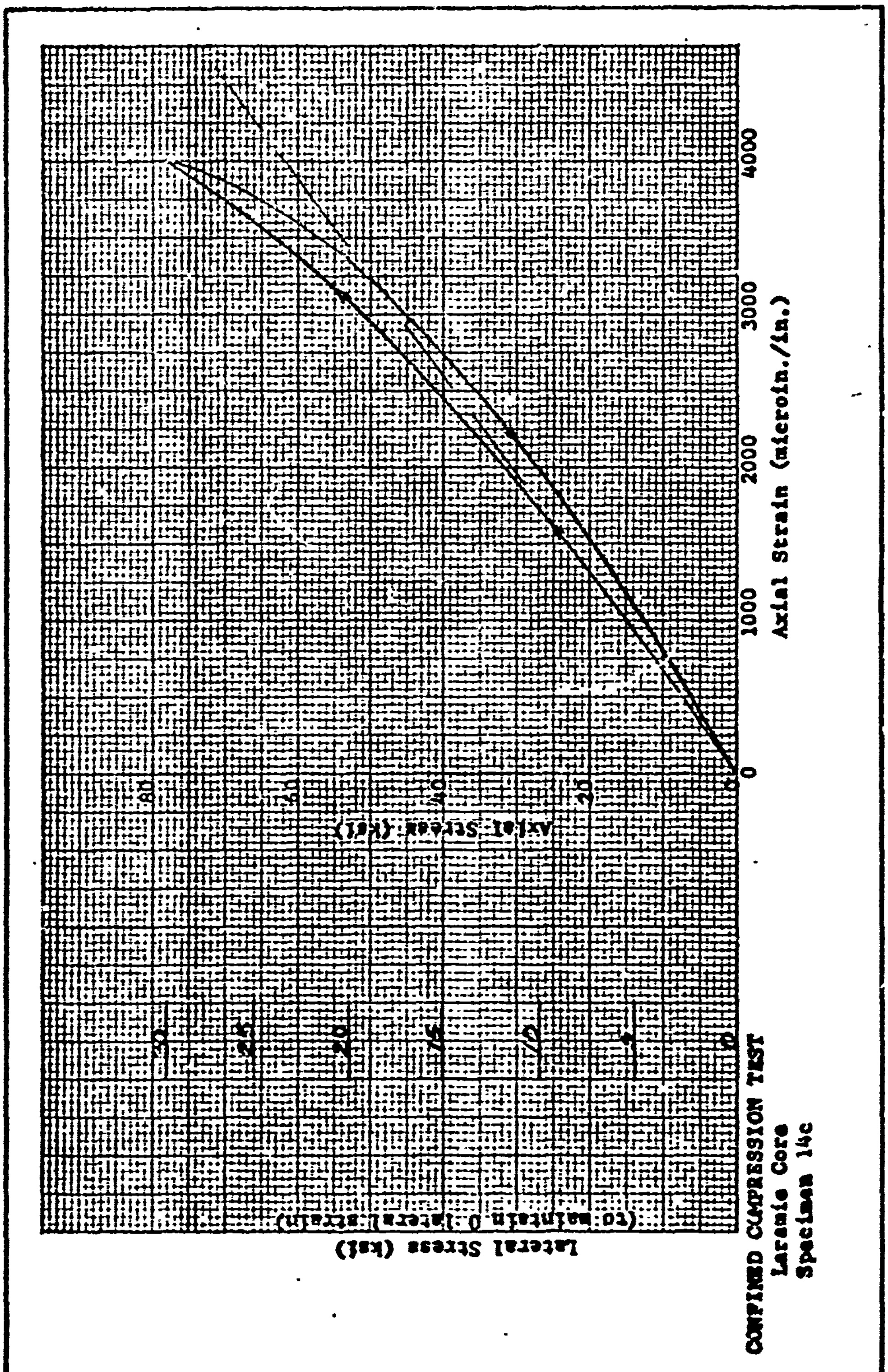
Posttest photograph triaxial specimen 2a

PLATE 23



CONFINED COMPRESSION TEST
Laramie Core
Specimen 1a

PLATE 24



CONFINED COMPRESSION TEST
Laramie Core
Specimen 14c
Axial Strain (microin./in.)
0
1000
2000
3000
4000
Axial Stress (ksi)
20
40
60
80
Lateral Stress (ksi)
(to maintain 0 lateral strain)
0
5
10
15
20
25
30

PLATE 25

APPENDIX C

DATA REPORT - HOLE CR-19 CORES

11 OCTOBER 1958

WARREN SITING AREA

Core No. 4 (Hole CR-19)

1. Sixteen pieces of core were received from the Warren area on 20 September 1968, designated CR-19 core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	14
A	2	16
A	3	17
A	4	18
B	5	83
B	6	84
B	7	85
B	8	85
B	9	86
B	10	87
B	11	88
C	12	190
C	13	191
C	14	192
C	15	193
C	16	194

2. The hole from which the core was taken was located in Albany County, Wyoming, township 19N, range 72W, section 3.

Warren Siting Area: Core No. 4 (Hole CR-19); Series I Tests

Results

Petrographic report

1. About 15 ft of NX rock core from three depths in hole CR-19 was received in September 1968 for testing. The four pieces of core used for petrographic examination are identified below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-4	1 (bottom part)	15.0	1/3
SAMSO-2 DC-4	8	85.4	1/3
SAMSO-2 DC-4	13 ([illegible] part)	191.0	1/3
SAMSO-2 DC-4	16 (bottom part)	194.9	1/3

2. All of the rock was coarse-grained but variations in crystal size caused variations in the appearance of the core. Pieces 5 through 15 had maximum crystal size, while pieces 1 and 2 had the smallest crystals and pieces 3 and 4 were intermediate in grain size. Piece 16 was unique in that the bottom portion was reddish rock instead of dark greenish gray rock.

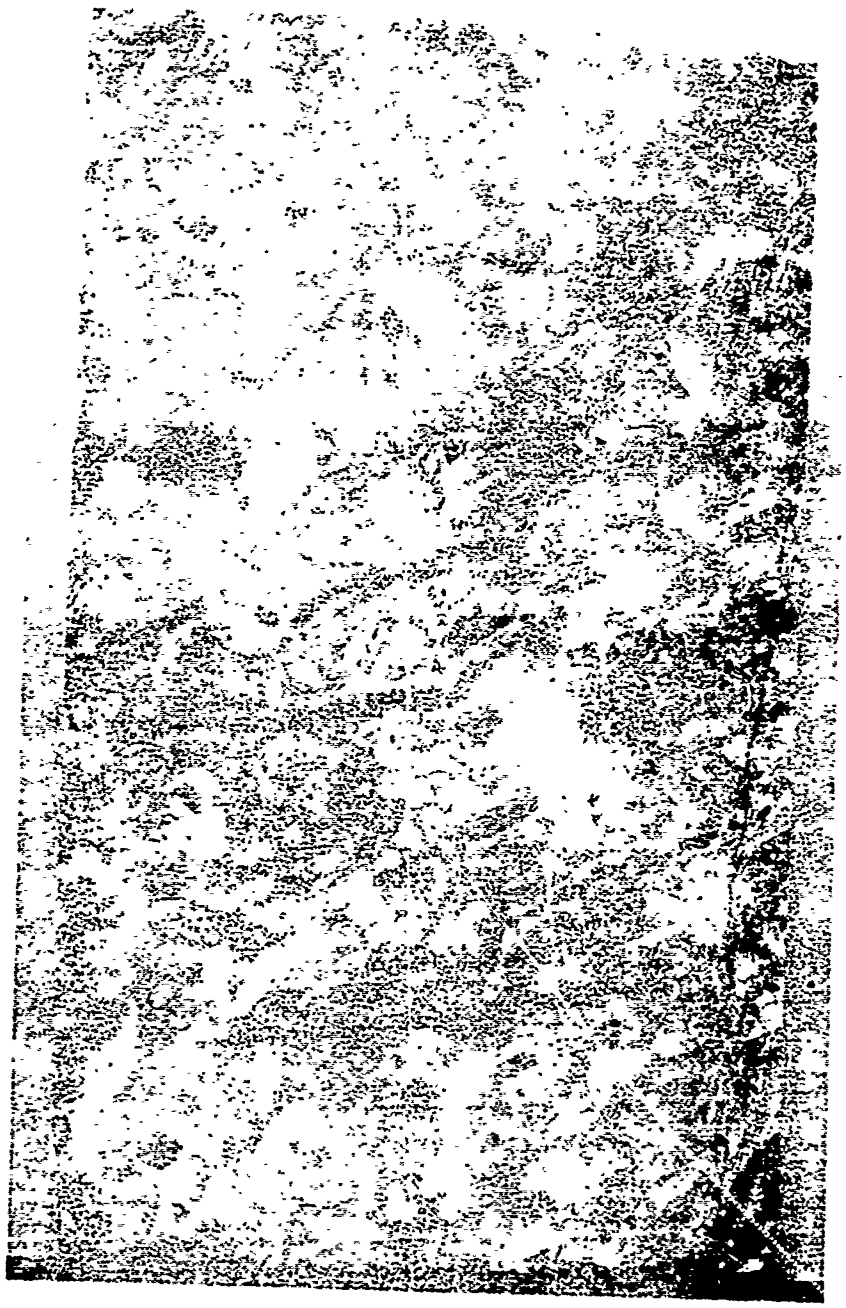
3. The petrographic work was performed as described in reports on previous samples that have been examined (SAMSO-2 DC-1 through 3).

4. The core consists of coarse-grained, dark-colored rock which consists largely of plagioclase feldspar with small amounts of biotite and what is probably a pyroxene mineral; there are even smaller amounts of iron-rich olivine, chlorite, kaolinite, quartz, calcite, magnetite, iron sulfide, muscovite, and possibly other unidentified minerals. The plagioclase occurs as euhedral phenocrysts; most of these are about 1/2 in. by 1/16 to 1/8 in. The other minerals in the rock have less well developed crystal shapes, except for a few plagioclase crystals forming inclusions in pyroxene or olivine.

5. This rock is classified as soda-diorite rather than anorthosite because the plagioclase is andesine rather than a more calcic type, which would justify the name anorthosite. The rock is essentially identical to the previous sample of soda-diorite from hole 1, Project S-11, 100 (Laramie core). The major difference in the rock from the two holes is that the present rock is not as coarse grained. Photographs 1 and 2 illustrate the appearance of this rock at 2X and at 1X.

6. There is an unusually large amount of magnetite in the lower portion of piece 16 just above the contact with the reddish rock.

7. The fine-grained, reddish igneous rock in piece 16 contains potassium feldspar, plagioclase feldspar, quartz, mica, and kaolinite. It is a rock of granitic composition, different from the soda-diorite (photograph 3).



Photograph 1. Sawed surface of piece 8 of SAMSO-2 DC-4. Magnification, [illegible].

...ing Area: Core No. 8 (Hole ...-12); Series I Tests

Photograph 2. Sawed surface of piece 8 of SAMSO-2 DC-4. Magnification, X1.

Photograph 3. Sawed surface of piece 16 of SAMSO-2 DC-4. Magnification, X1. The lower part of the core is the reddish rock which is unlike the rest of the core.

8. Some of the fracture surfaces are coated with a thin layer of blackish material. A sample from the fracture ending piece 13 was identified as vermiculite.

9. Thin sections and ground surfaces of the rock examined in polarized light or with a stereomicroscope show fairly extensive alteration of all of the constituents except the predominant andesine feldspar.

Schmidt number, specific gravity, porosity, and tensile strength

10. Three specimens from each depth interval were selected for the basic tests. Results are given below:

Core	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
		Sample A - 15-ft Depth			
1b	55.8	4.16	2.787	0.0	1300
2b	51.9	3.74	2.864	0.1	1070
4a	54.5	4.30	2.811	0.0	1030
Avg	54.1	4.07	2.821	0.0	1130
		Sample B - 85-ft Depth			
5a	60.5	4.02	2.846	0.1	1170
7a	59.1	4.03	2.895	0.0	1240
9a	58.9	3.30	2.887	0.1	1530
Avg	59.5	3.78	2.876	0.1	1310
		Sample C - 190-ft Depth			
12b	55.0	5.90	2.848	0.1	1630
13a	56.7	5.76	2.873	0.0	1140
15b	57.4	5.08	2.906	0.1	1280
Avg	56.4	5.58	2.876	0.1	1350

11. Indications are that the CR-19 core is a very hard, strong material. Schmidt numbers of 60 are encountered only with the toughest of rock. The rock in the upper elevation (15-ft depth) is only slightly different from that from the lower two intervals tested.

Shear tests

12. Direct single plane shear tests were conducted on three samples from the 85-ft depth interval and one sample from the 15-ft depth interval. Shear strengths of 1530, 1580, and 1510 psi (average 1560) were obtained on samples 9a, 9b, and 11a, respectively. One test, on sample 3b, from the upper elevation resulted in a shear strength of 1060 psi. A posttest photograph of the test specimens is given in plate 1.

Unconfined compressive strength tests

13. Conventional unconfined compressive strength tests were conducted on specimens from the upper and lower depth intervals and cyclic compressive tests on specimens from the middle depth interval. Results are given below:

Core No.	Depth, ft	Unconfined Compressive Strength, psi
1a	14	24,500
2a	16	30,600
3a	17	20,100
Avg	15	25,070
5b	83	27,700
7b	85	30,900
9b	86	27,900
Avg	85	28,830
12a	190	25,400
13b	191	25,700
15a	193	22,900
Avg	191	24,670

There is no significant change of strength with depth; however, the material is quite variable as indicated by the wide range of strengths (20,000 to 30,000 psi).

14. All specimens had two vertical and two horizontal electrical resistance strain gages affixed in order to measure strain during testing. The cycled specimens were unloaded at 5000-psi intervals. Stress-strain curves are given in plates 2-10. The stress-strain

relationships were linear almost to failure; hysteresis was negligible. To compute the deformation moduli, a tangent at 50 percent of the ultimate strength was constructed as a dashed line on the stress-strain curves. A posttest photograph of the test specimens, plate 11, shows the nature of failure, steep sided coning.

Moduli of deformation

15. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on three samples by the dynamic (fundamental frequency) method and on the unconfined compressive strength specimens statically at approximately 50 percent of the ultimate strength. Results are given below:

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
1	12.43	4.87	9.42	0.28
10	15.73	5.76	20.17	0.37
15	13.66	5.11	14.23	0.34
		Statically		
1a	14.20	5.55	10.75	0.28
2a	13.60	5.27	10.79	0.29
3a	13.40	5.04	13.14	0.33
5b	13.20	4.92	13.75	0.34
7b	14.50	5.53	12.72	0.31
9b	15.50	5.92	13.60	0.31
12a	13.90	5.39	11.03	0.29
13b	15.10	5.94	10.94	0.27
15a	13.40	5.04	13.14	0.33
Avg Static	14.09	5.40	12.21	0.30

16. The static and dynamic results agree well with the exception of the dynamic bulk modulus for core No. 10 which is unusually high. The moduli are significantly high for rock, higher than many rocks of comparable strength. Apparently this is a very rigid material.

Velocity measurements

17. The compressional wave velocity was determined directly as the sonic propagation velocity, and the shear wave velocity was determined from the torsional frequency obtained in the moduli determinations.

Warren Siting Area: Core No. 4 (Hole CR-19); Series I Tests

Core No.	Compressional Velocity, fps	Shear Velocity, fps
1	20,405	11,405
10	20,490	11,720
15	20,825	11,355
Avg	20,570	11,490

The shear velocity is approximately 56 percent of the compressional velocity.

Conclusions

18. The CR-19 core is identified as a soda-diorite, essentially identical to the Laramie core except that it is not as coarse grained as the Laramie core. The CR-19 core is an unusually heavy, rigid material which is rather variable in strength throughout the intervals tested. Consensus results of some physical properties compared to the Laramie core are:

Property	Laramie Core	CR-19 Core
Specific gravity	2.72	2.85
Percent porosity	0.0	0.1
Compressive strength, psi	21,600	26,190
Tensile strength, psi	1,400	1,270
Young's modulus, psi x 10^6	11.8	14.1
Compressional wave velocity, fps	19,800	20,570

sts

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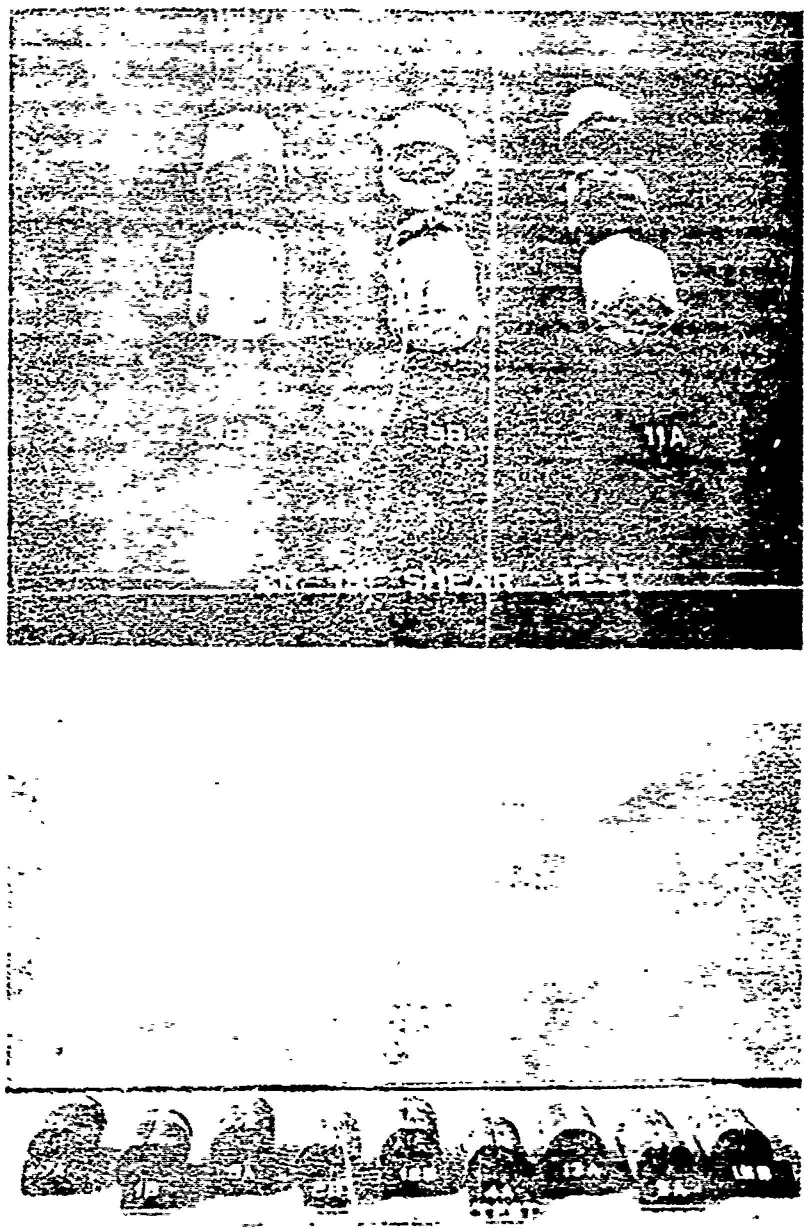
grained
igid
intervals
ed to the

R-19 Cord

2.85
0.1
26,190
1,270
14.1
20,570



Posttest Photographs

PLATE 1

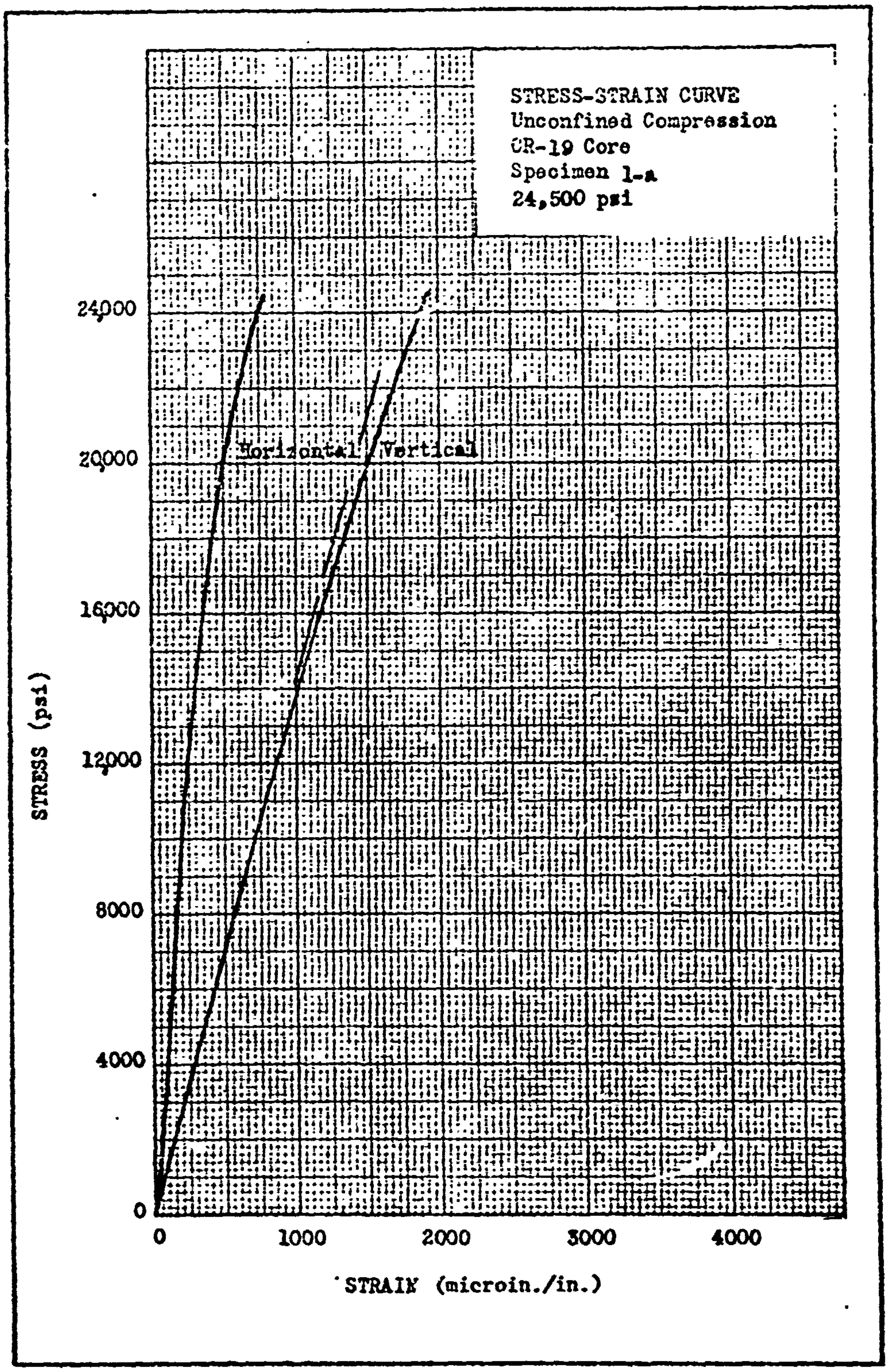

STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 1-a
24,500 psi
Horizontal
Vertical
STRESS (psi)
0
4000
8000
12000
16000
20000
24000
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 2

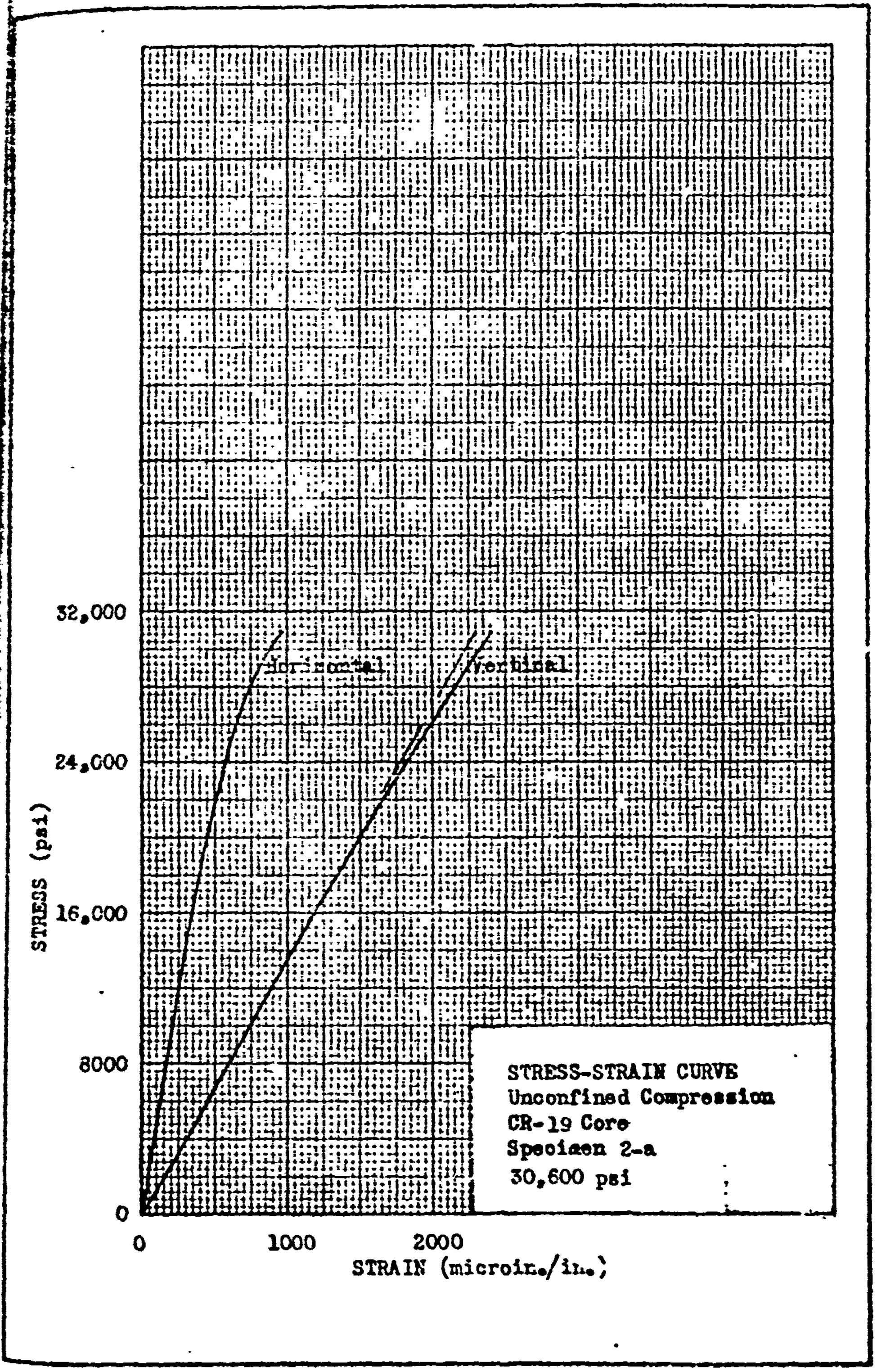

32,000
24,000
16,000
8000
0
STRESS (psi)
0
1000
2000
STRAIN (microin./in.)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 2-a
30,600 psi

PLATE 3

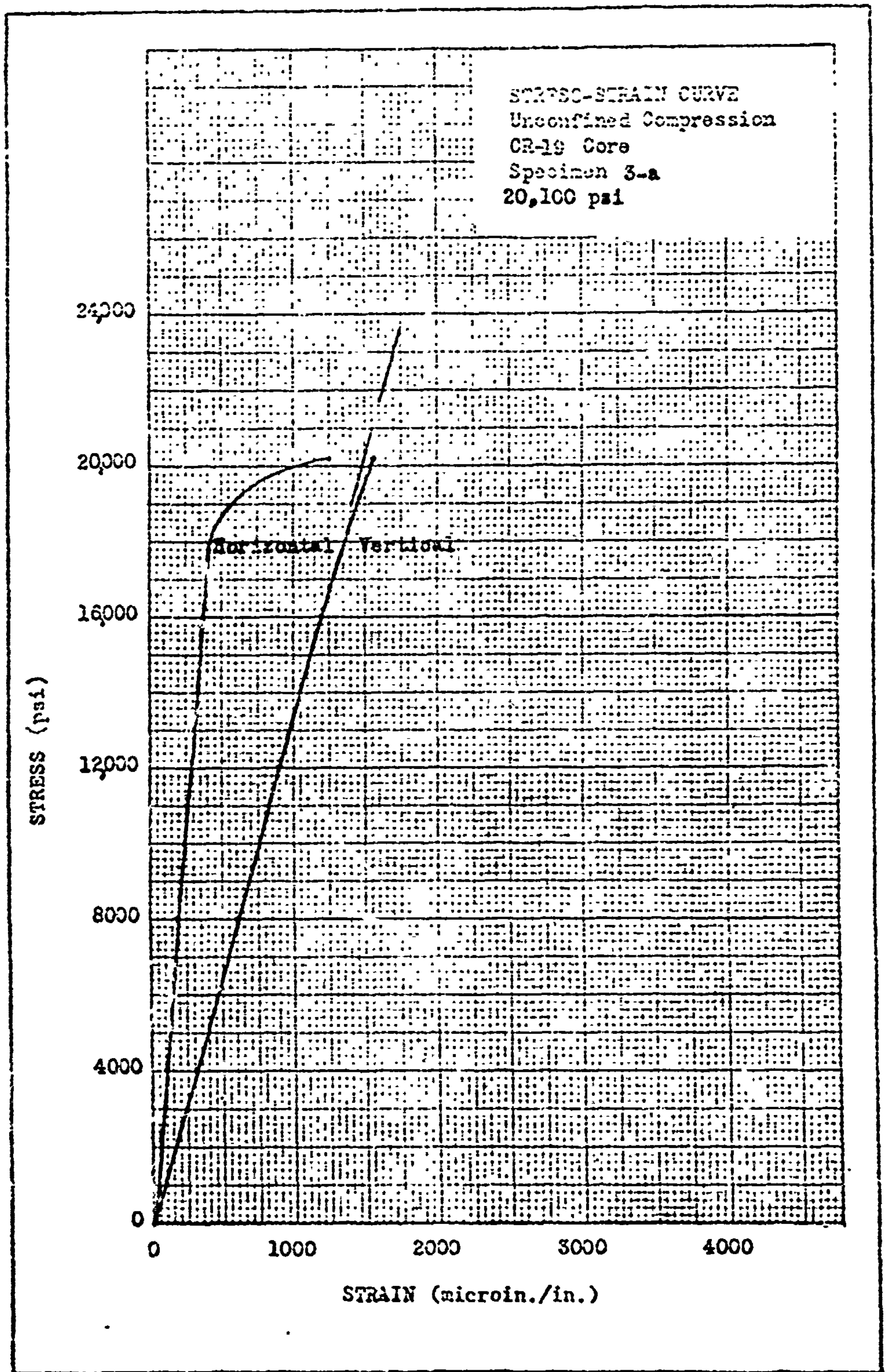

STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 3-a
20,100 psi
Horizontal
Vertical
STRESS (psi)
0
4000
8000
12000
16000
20000
24000
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 4

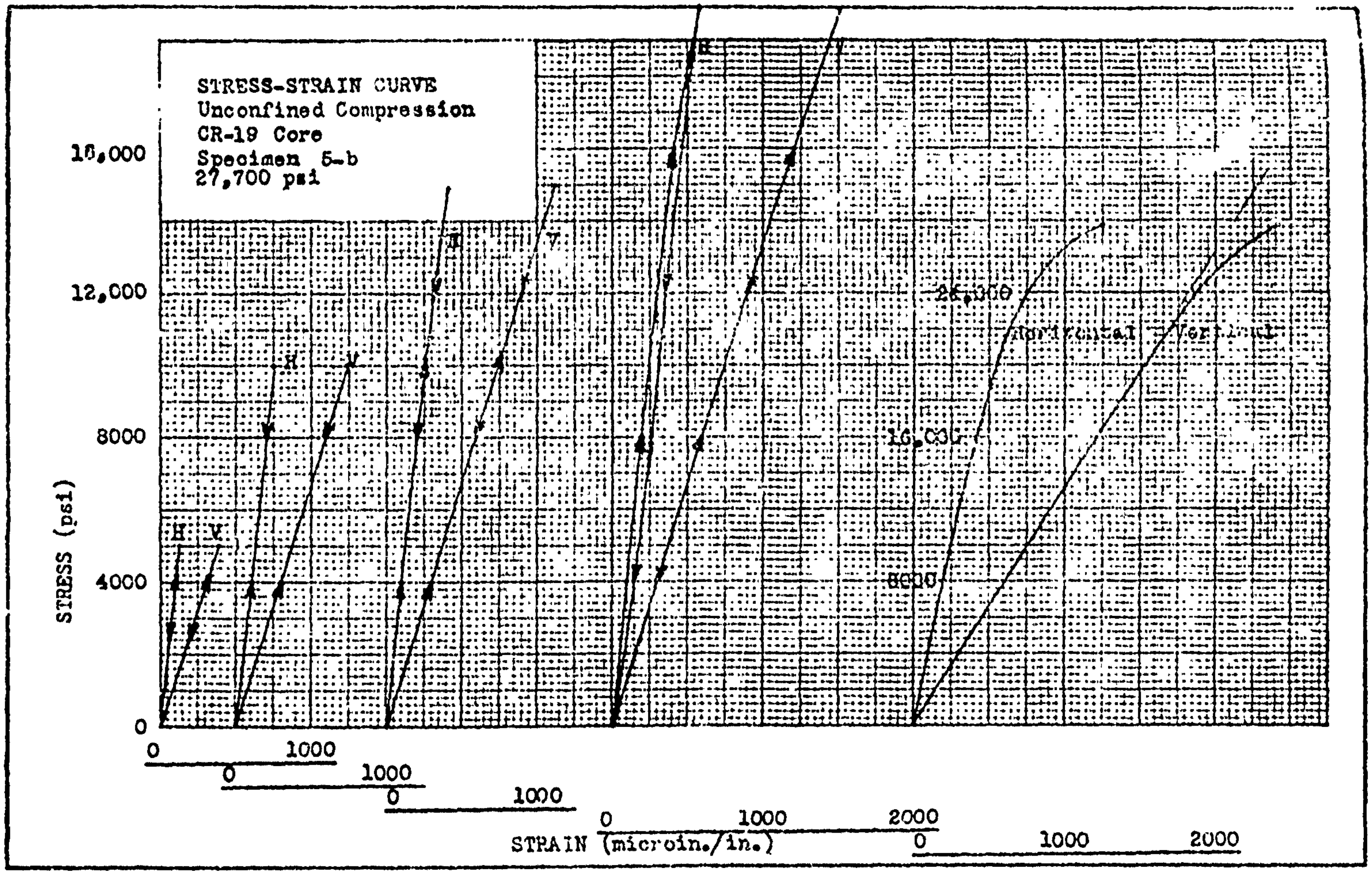
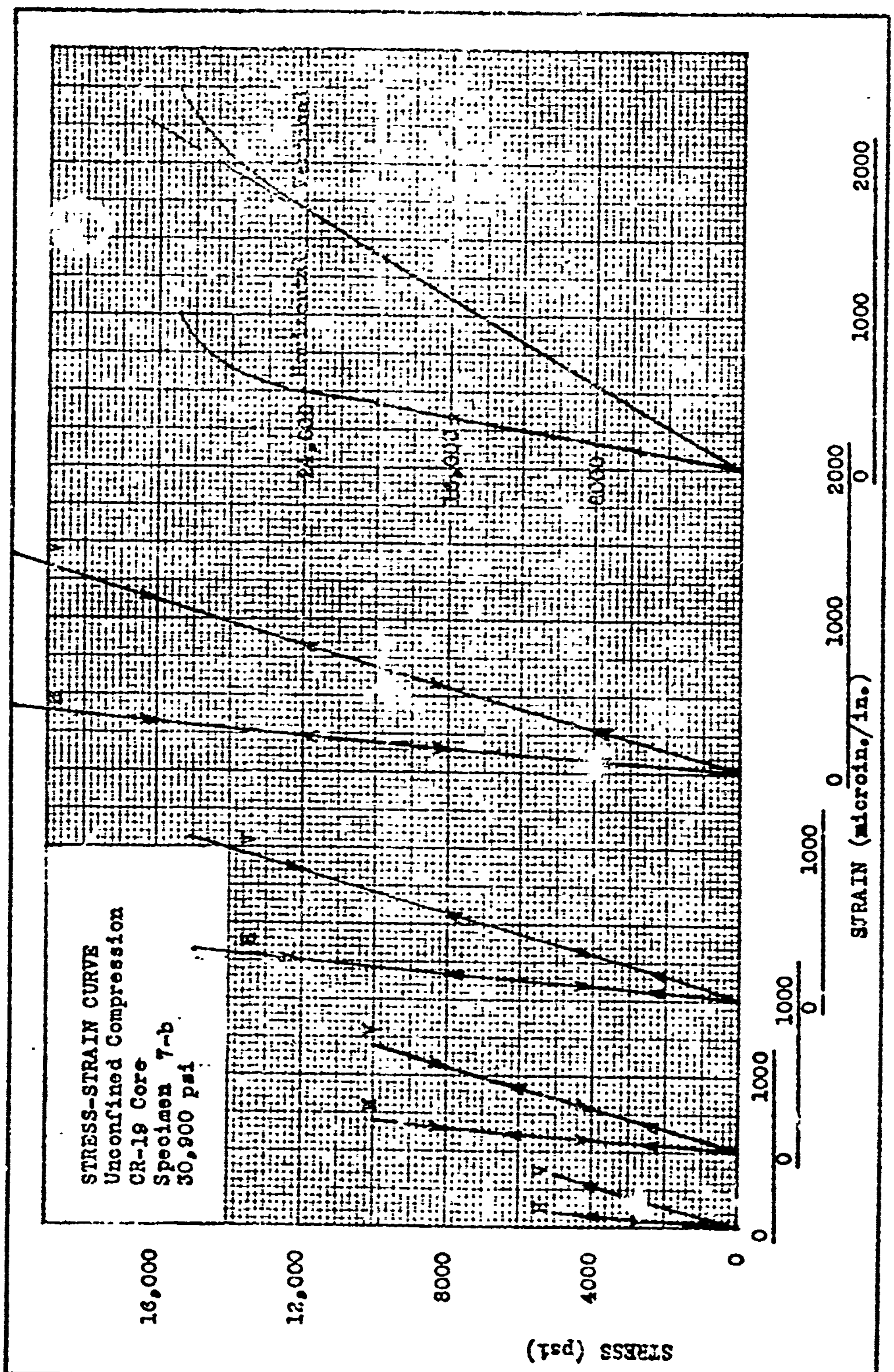
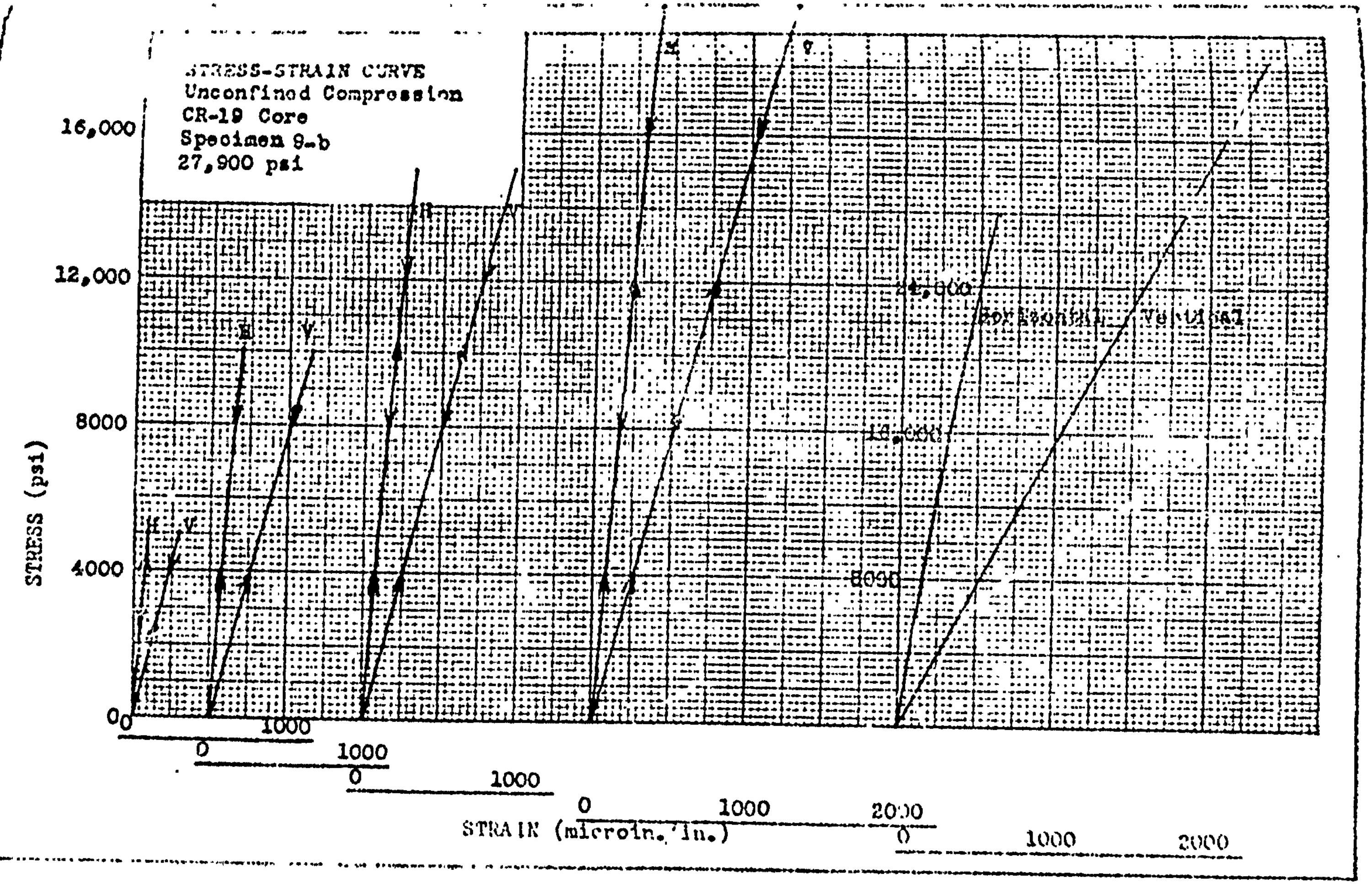

STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 5-b
27,700 psi
STRESS (psi)
STRAIN (microin./in.)
16,000
12,000
8000
4000
0
1000
2000
H
V
24,000
16,000
8000
Horizontal
Vertical

PLATE 5



STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 7-b
30,900 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
0
1000
0
1000
0
1000
2000
0
1000
2000
H
V
H
V
H
V
H
V
24,600

PLATE 6


STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 9-b
27,900 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
1000
2000
H
V
Horizontal
Vertical

PLATE

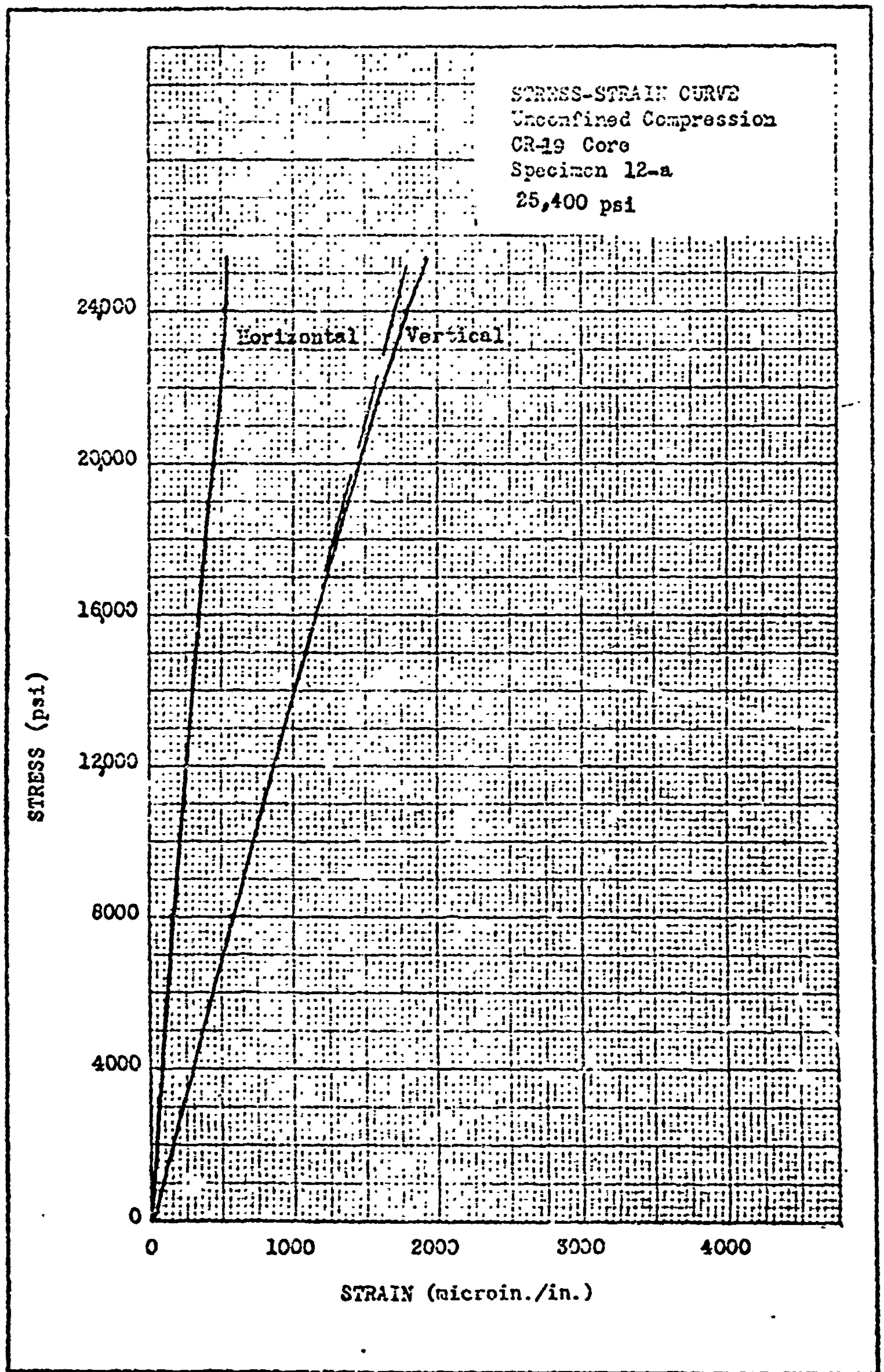

STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 12-a
25,400 psi
Horizontal
Vertical
24000
20000
16000
12000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 8

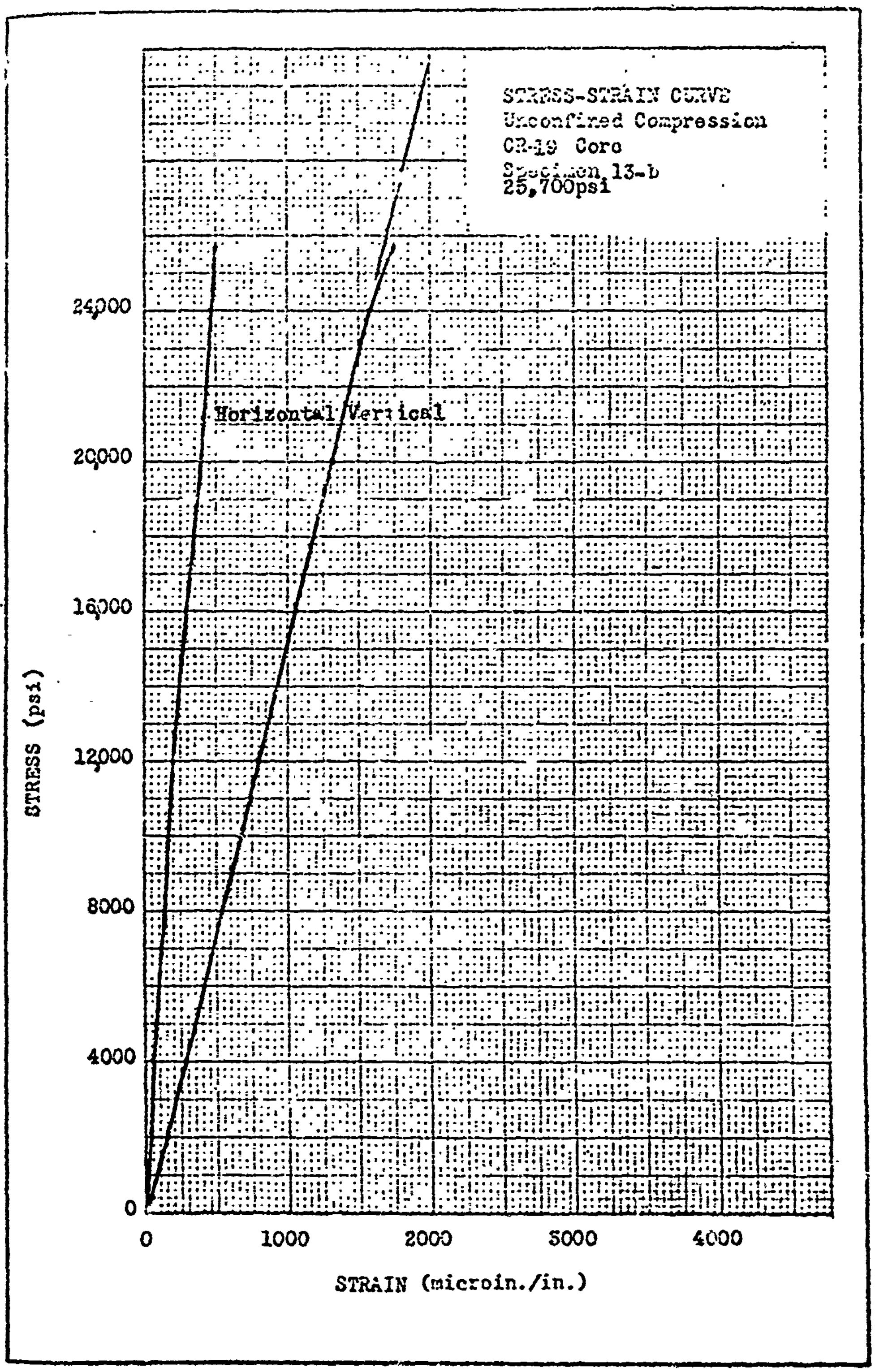

STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 13-b
25,700psi
Horizontal
Vertical
STRESS (psi)
24000
20000
16000
12000
8000
4000
0
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 9

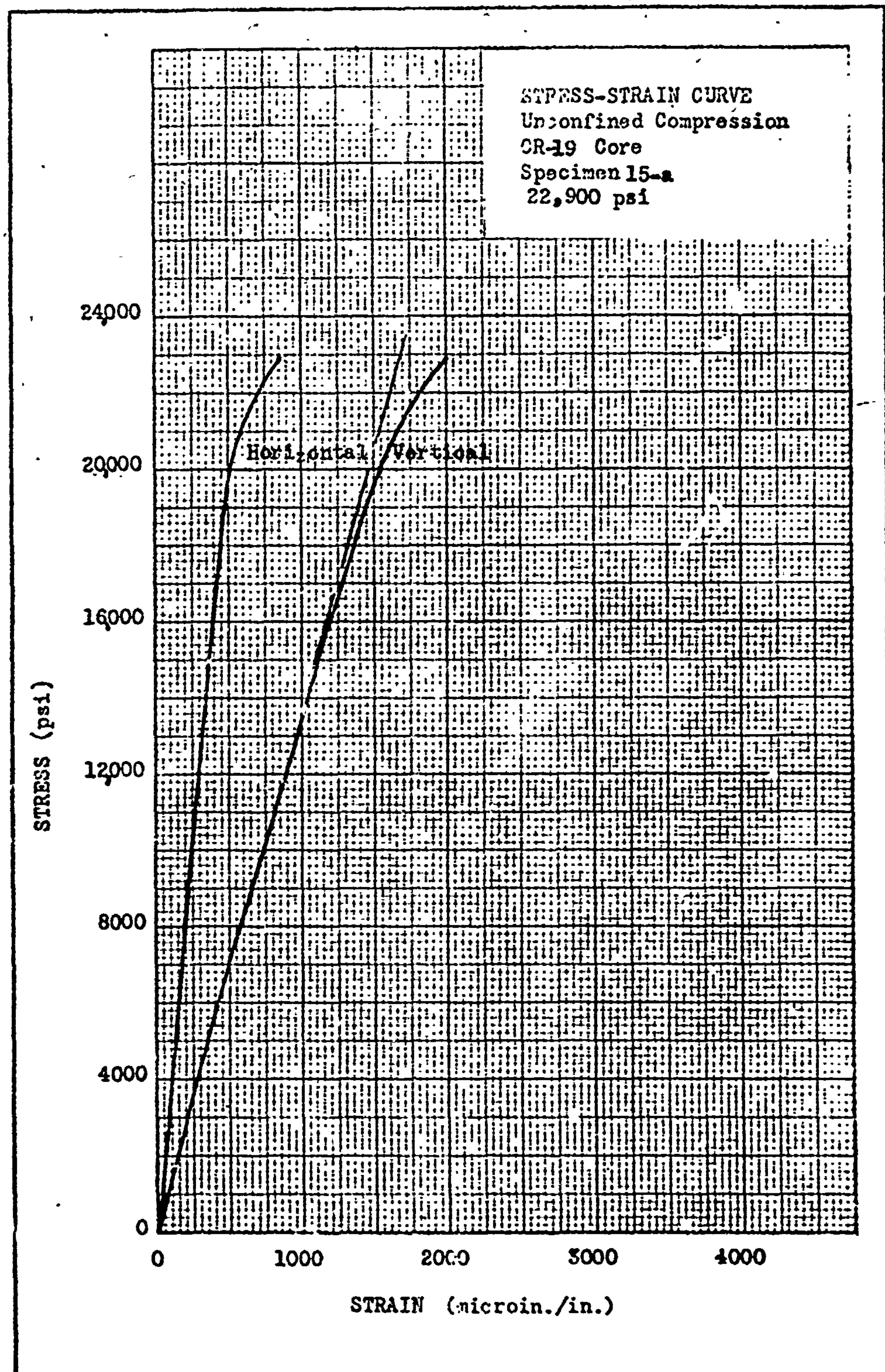
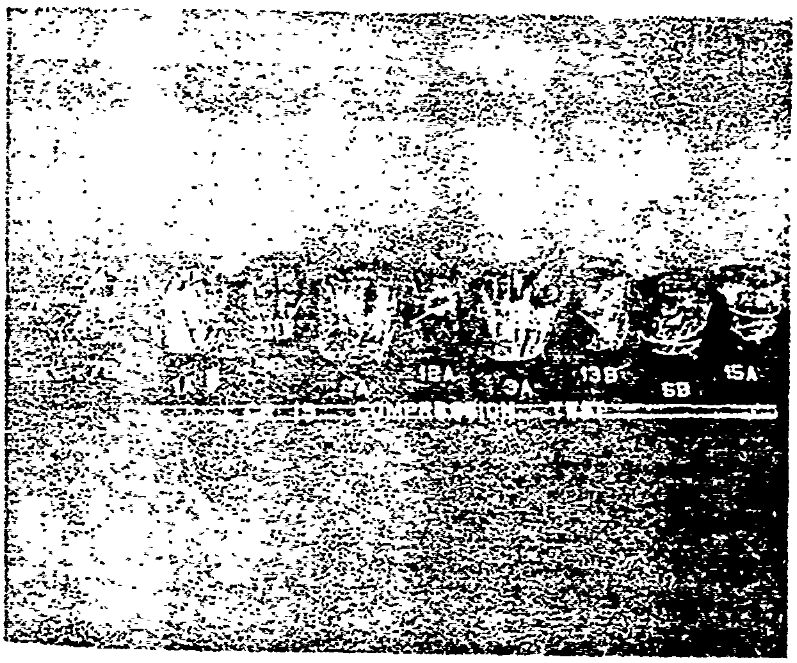

STRESS-STRAIN CURVE
Unconfined Compression
CR-19 Core
Specimen 15-a
22,900 psi
Horizontal
Vertical
24000
20000
16000
12000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 10



Posttest Photograph

PLATE 11

APPENDIX D

DATA REPORT - HOLE CR-32 CORES

15 OCTOBER 1968

WARREN SITING AREA

Core No. 5 (Hole CR-32)

1. Eleven pieces of core were received from the Warren area, designated CR-32 core, on 23 September 1968. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	158
A	2	159
A	3	160
A	4	161
A	5	162
A	6	163
A	7	164
A	8	165
A	9	168
A	10	170
A	11	174

2. The hole from which the core was taken was located in Albany County, Wyoming, township 17N, range 72W, section 35. All core was drilled vertically. Specimens were cut as required for the various tests; each segment of the specimen was given a letter designation signifying the section cut; for example, specimen 7a was the first test piece cut from specimen 7. Tests were conducted identical to previous tests on the Warren area core.

Warren Siting Area: Core No. 5 (Hole CR-32); Series I Tests

Results

Petrographic examination

3. One box of NX rock core fragments representing depths 157.9 through 176.5 ft from hole CR-32 was received in September 1968 for testing. The pieces used for the petrographic examination are shown below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-5	3B	161	1/3
SAMSO-2 DC-5	4A	161.4	1/3
SAMSO-2 DC-5	4B	161.7	1/3
SAMSO-2 DC-5	8	162	1/4

4. The test procedure was similar to that followed for previous samples in this series.

5. The core consisted of light-colored, grayish igneous rock and of black schist. The approximate disposition of these materials is shown below:

Interval, ft	Description
157.9 - 161	Igneous rock.
161 - 162	Black schist and contact with igneous rock; the contact surface is dipping about 45 degrees.
162 - 166.4	Igneous rock.
166.4 - 176.5	Black schist.

6. All of the core is badly fragmented due to the presence of numerous horizontal, vertical, and steeply dipping fracture surfaces. Some of these fractures are open and some are not, but almost all of them were present prior to drilling; the presence of a thin coating of white or pinkish calcite on most of these broken surfaces is proof of their age. The core fragments of schist tend to be about 1 to 2 in. long, and the core fragments of the igneous rock tend to be about 4 in. long, although there are longer pieces of both types.

7. The rock described in the field log as coarse-grained, medium gray anorthosite is the grayish igneous rock and the material described as some combination of the terms fine-grained, black, sandstone texture, or broken is the black schist.

8. Photograph 1 illustrates the appearance of the two rock types, and photograph 2 shows the joint or fracture patterns in the igneous rock.

9. The igneous rock is medium-grained with some grains ranging up to 1/4 in., but most are more like 1/16 in. in size. The rock is composed largely of plagioclase feldspar with smaller amounts of hornblende and biotite; there is also some chlorite and an opaque mineral and perhaps some kaolinite. Most of the plagioclase shows some alteration. The plagioclase is labradorite with a composition of about $Ab_{40}An_{60}$. This rock is a lime-diorite by the terminology of Shand.* This material was logged as anorthosite in the field. Shand prefers to restrict the term anorthosite to rocks "composed almost entirely of feldspar."

10. The black schist is composed largely of hornblende, chlorite, and montmorillonitic clay; there is also a little plagioclase feldspar, and there may be some kaolinite. There is probably some mica, but it is very minor in amount.

11. It is not possible to determine which is the host rock and which the intrusive rock from the limited structure shown by the core. All of the specimens selected for the physical tests were lime-diorite; none of the black schist samples were large enough to secure test specimens.

Schmidt number, specific gravity, porosity, and tensile strength

12. Due to the highly fractured nature of the samples, only three specimens could be secured for the basic tests. Results are given below:

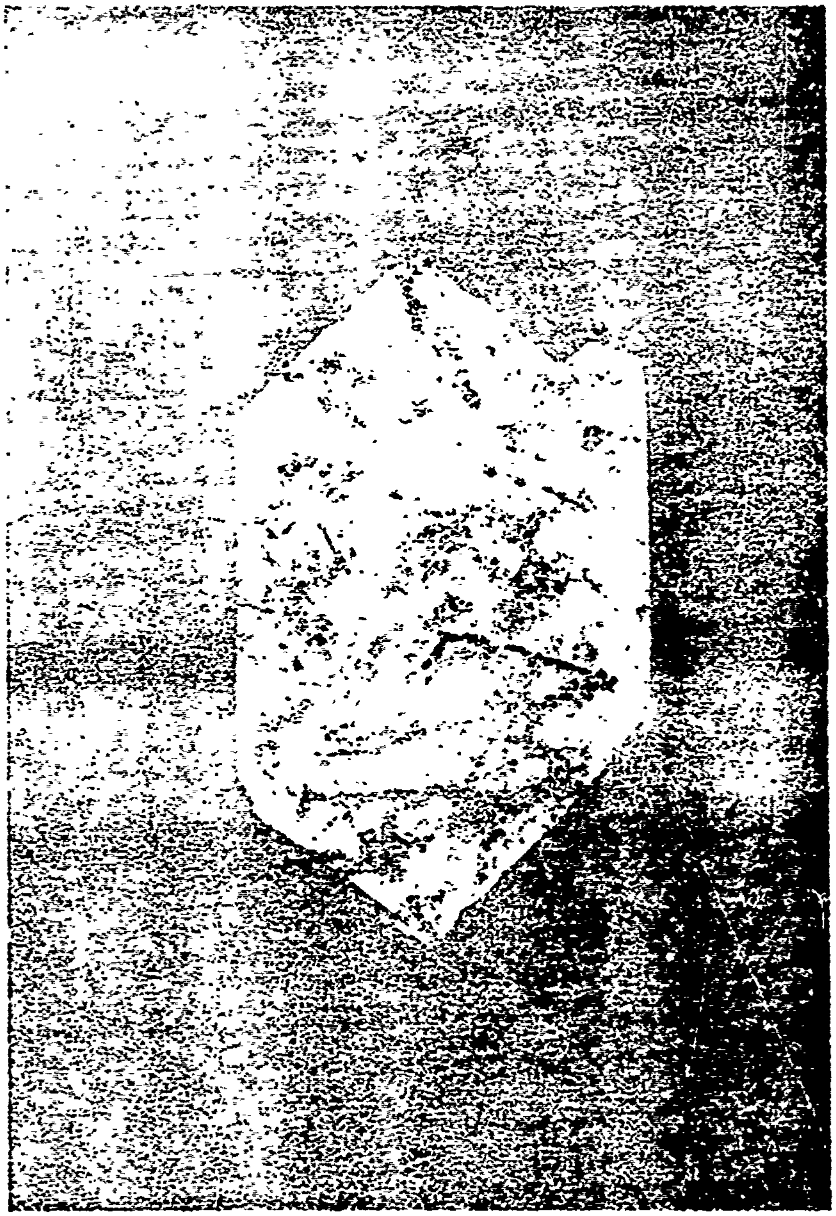
Specimen	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
4d	54.5	4.66	2.763	0.0	1290
5b	56.9	5.19	2.754	0.2	1460
6b	53.1	5.03	2.756	0.0	1580
Avg	54.8	4.96	2.758	0.1	1440

The rock tested is apparently a hard, dense material. However, the indication of high quality rock by these basic tests should not be

* Shand, S. J., Eruptive Rocks, 3d edition, John Wiley and Sons, New York, N. Y., 1947.

Siting Area: Core No. 5 (Hole CR-32); Series I Tests

Photograph 1. Sawed surface of piece 4a from core hole CR-32, depth about 161.4 ft, natural size. Lower left and upper right areas are black schist.



Photograph 2. Sawed surface of piece 8 from core hole CR-32, depth about 156 ft, natural size. Ends of core indicate pair of intersecting joint systems.

construed as evidence of a competent material throughout. The entire length of sample received was highly fractured; locating sufficient core for test specimens was difficult.

Shear tests

13. The shortage of suitable test samples prevented shear testing of the CR-32 core.

Unconfined compressive tests

14. Conventional unconfined compressive tests were conducted on three specimens. Results are given below:

Specimen No.	Depth, ft	Unconfined Compressive Strength, psi
5a	162	29,900
6a	163	21,700
7a	164	30,800
Avg	163	27,470

As indicated in the basic tests, the material tested is fairly competent, although quite variable. Specimen No. 5a was only 3-1/2 in. long; therefore, the indicated strength may be high for this particular test. A posttest photograph of the test specimens, Plate 1, shows the nature of failure, steep sided coning.

Moduli of deformation

15. Stress-strain curves for the unconfined compressive tests are given in plates 2, 3, and 4. The axial (vertical) stress-strain relationship is virtually linear. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on specimen 6 by the dynamic (fundamental frequency) method and on the unconfined compressive strength specimens statically at approximately 50 percent of the ultimate strength. Results are given below:

Specimen No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
6	9.63	4.54	3.55	0.06

(Continued)

Warren Siting Area: Core No. 5 (Hole CR-32); Series I Tests

(Continued)

Specimen No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Statically		
5a	12.50	5.04	8.01	0.24
6a	12.00	4.62	10.00	0.30
7a	11.50	4.53	8.33	0.27
Avg Static	12.00	4.73	8.78	0.27

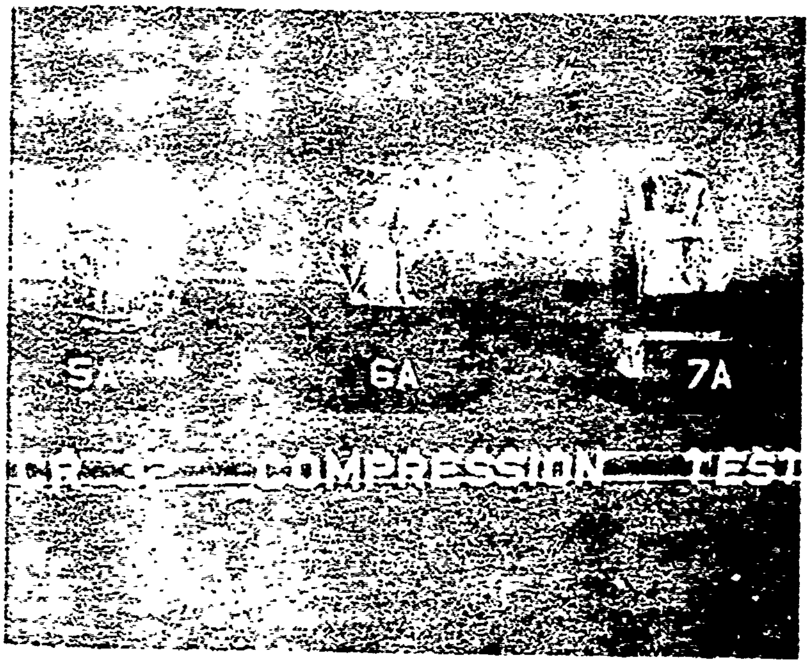
Velocity measurements

16. The compressional velocity was determined directly on specimen No. 6 to be 15,480 fps. The shear velocity, 10,980 fps, determined from the torsional frequency, is 71 percent of the compressional velocity.

Conclusions

17. The rock from hole CR-32 was a highly fractured material consisting of a light igneous rock, lime-diorite, and black schist. Locating sufficient samples for testing was difficult. Consensus results of tests on the lime-diorite, given below, do not reflect the incompetent nature of the material as a whole.

Property	Lime-Diorite
Specific gravity	2.76
Percent porosity	0.1
Compressive strength, psi	27,470
Tensile strength, psi	1,440
Young's modulus, psi x 10^6	12.00
Compressional wave velocity, fps	15,480



Posttest Photograph

PLATE 1

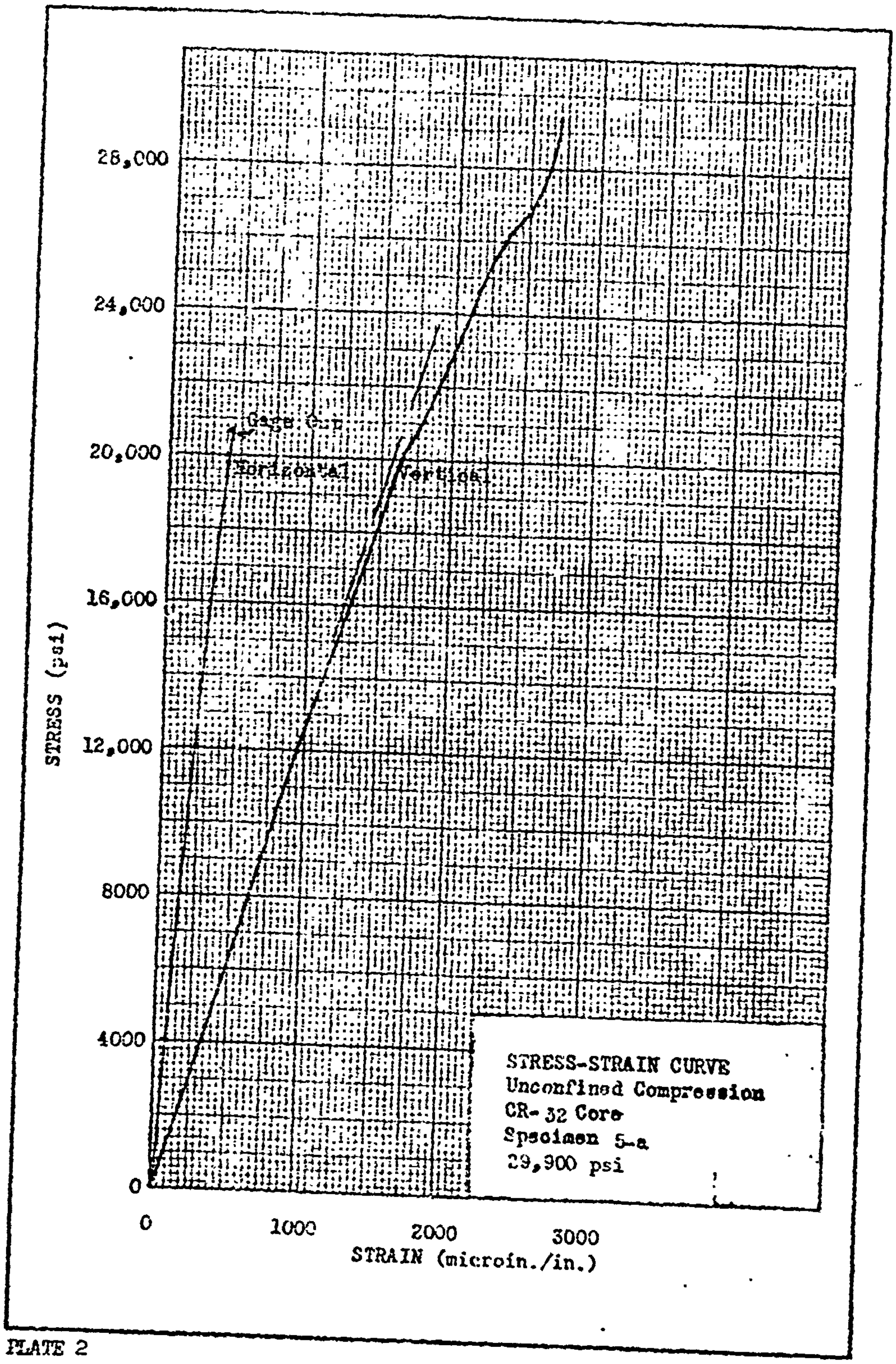

28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
Gage
Horizontal
Vertical
0
1000
2000
3000
STRAIN (microin./in.)
STRESS-STRAIN CURVE
Unconfined Compression
CR-32 Core
Specimen 5-a
29,900 psi

PLATE 2

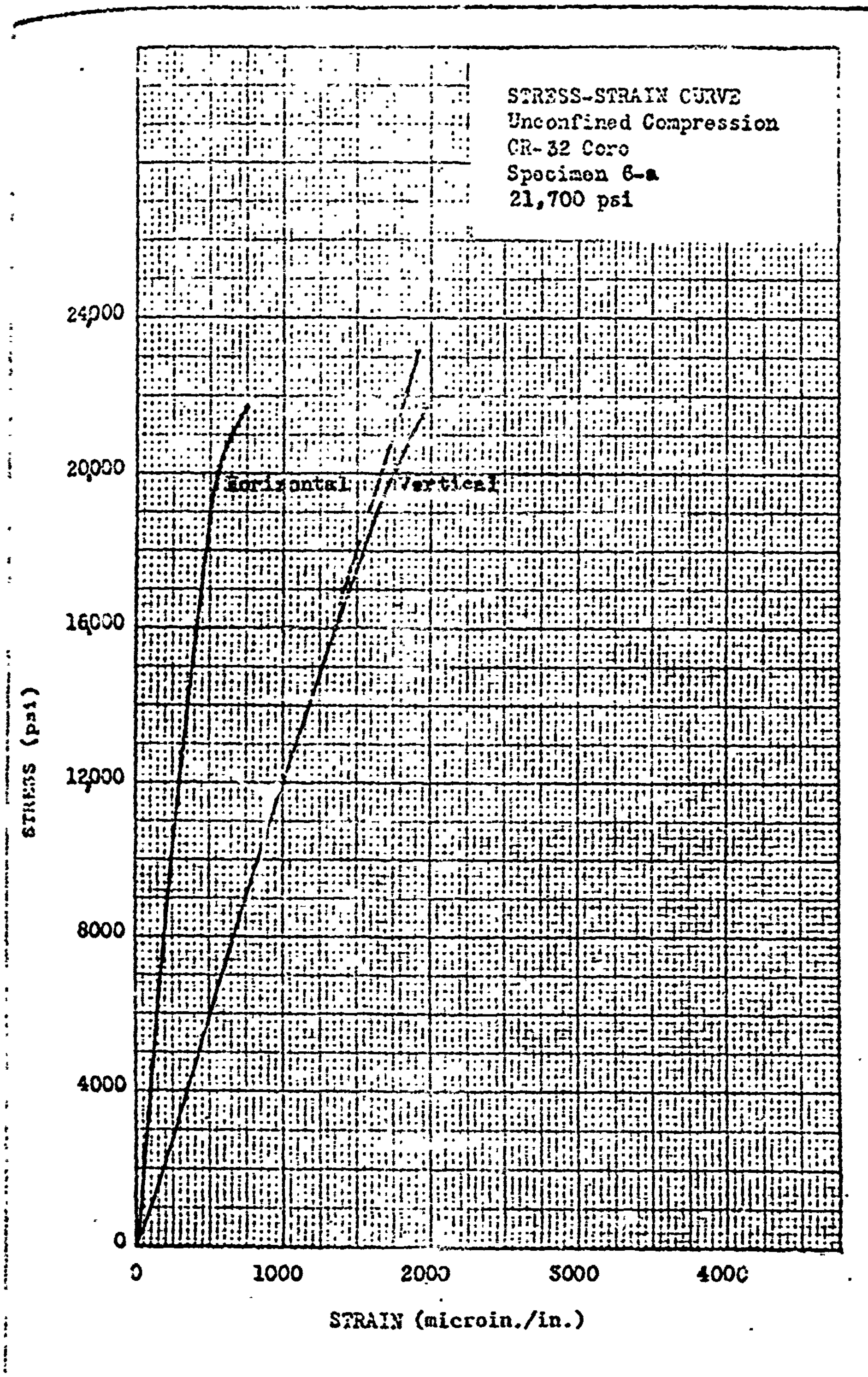
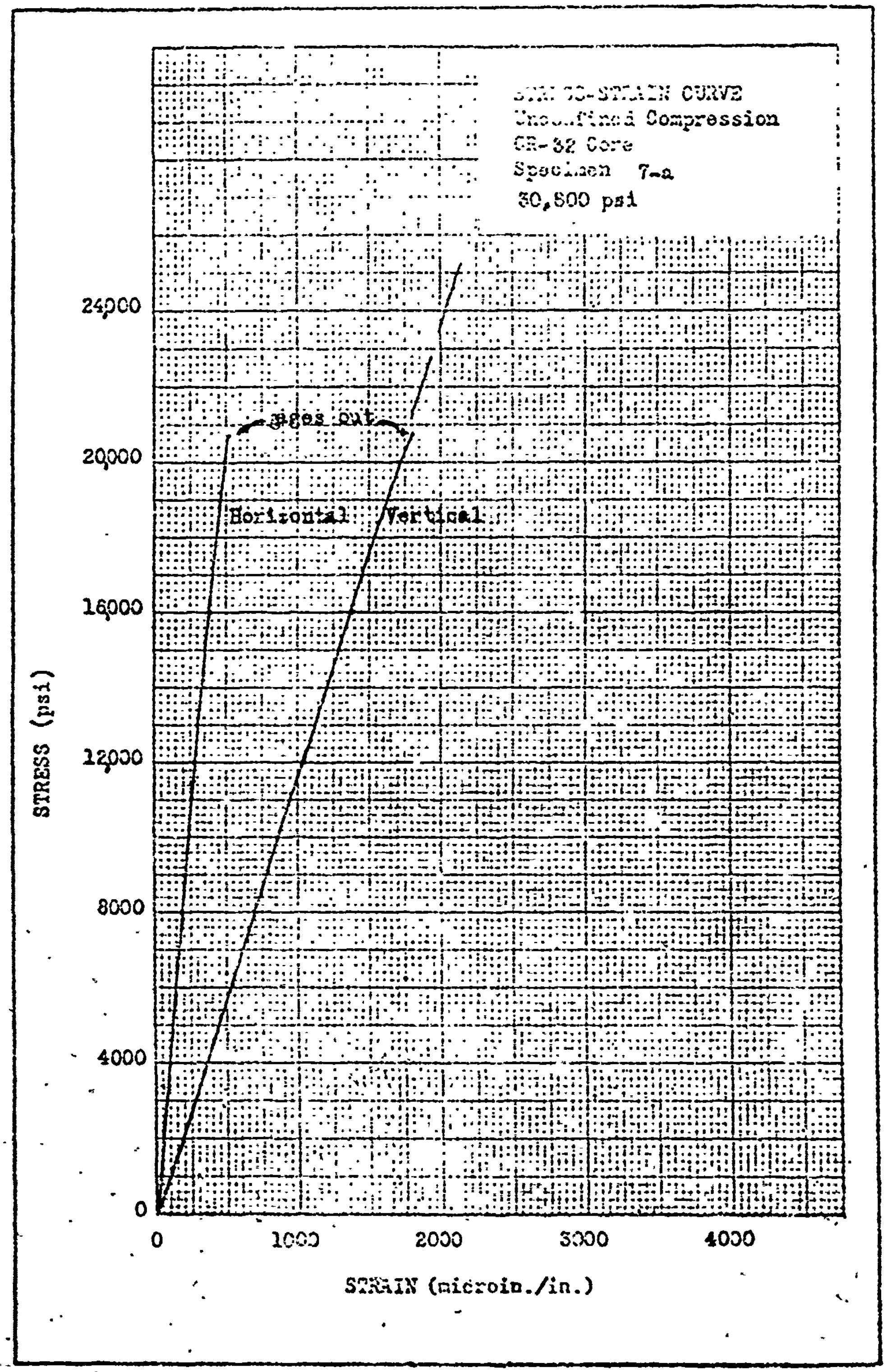

STRESS-STRAIN CURVE
Unconfined Compression
CR-32 Core
Specimen 6-a
21,700 psi
Horizontal
Vertical
STRESS (psi)
24000
20000
16000
12000
8000
4000
0
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 3



STRESS-STRAIN CURVE
Unconfined Compression
Specimen 7-a
30,800 psi
gages out
Horizontal
Vertical
24000
20000
16000
12000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 4

APPENDIX E

DATA REPORT - HOLE CR-4 CORES

4 OCTOBER 1968

WARREN SITING AREA

Core No. 3 (Hole CR-4)

1. Eighteen pieces of core were received from the Warren area, designated CR-4 core, on 17 September 1968. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	21
A	2	22
A	3	27
A	4	32
A	5	33
A	6	34
B	7	55
B	8	55
B	9	56
B	10	57
B	11	58
B	12	59
C	13	181
C	14	182
C	15	183
C	16	184
C	17	184
C	18	185

2. The hole from which the core was taken was located in Albany County, Wyoming, township 27N, range 74W, section 3. All core was drilled vertically. Specimens were cut as required for the various tests; each segment of the specimen was given a letter designation signifying the section cut; for example, specimen 7a was the first test piece cut from specimen 7. Tests were conducted identical to previous tests on the Warren area core.

Results

Petrographic examination

1. About 15 ft of NX rock core from three depths in hole CR-4 in Albany County, Wyoming, was received in September 1968 for testing. The specimens used for petrographic examination are identified below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-3	1	20.8	1/3
SAMSO-2 DC-3	9	66.7	1/3

2. The rock in pieces 1 through 6 was medium-grained and pink, while that in the rest of the pieces (7 through 18) was more gray than pink in color. One end of piece 18 was transitional back to pink, coarse-grained material.

3. The petrographic work consisted of photography, X-ray diffraction examinations, and microscopical examinations using samples and procedures as described in previous reports for the samples from core hole 1, Project S-11, 100 and from core hole CR-42.

4. Pieces 4 and 6 each contained nearly vertical open fractures. The fragmented condition and appearance of piece 4 indicated that it was quite weathered.

5. Piece 1 is composed primarily of quartz and plagioclase and microcline feldspars with minor amounts of biotite and chlorite and probably trace amounts of a pyroxene. Piece 9 differs from piece 1 in that potassium feldspar (microcline) is only a minor constituent. All of the rock except the bottom of piece 18 is medium-grained. The individual grains do not show crystal faces, with a few exceptions, and range from about 1/16 to 1/4 in. in maximum dimension (photograph 1).

6. All of the plagioclase feldspar shows some alteration, probably to sericite. There is little or no alteration of the potassium feldspar.

7. All of the rock was logged in the field as granite. The laboratory work indicates that, while granite is a suitable name for the pinkish rock of pieces 1 through 6, the grayish rock of pieces 7 through 17 is tonalite according to the classification of Shand* rather than granite, because there is not enough potassium feldspar (microcline) to justify the name granite.

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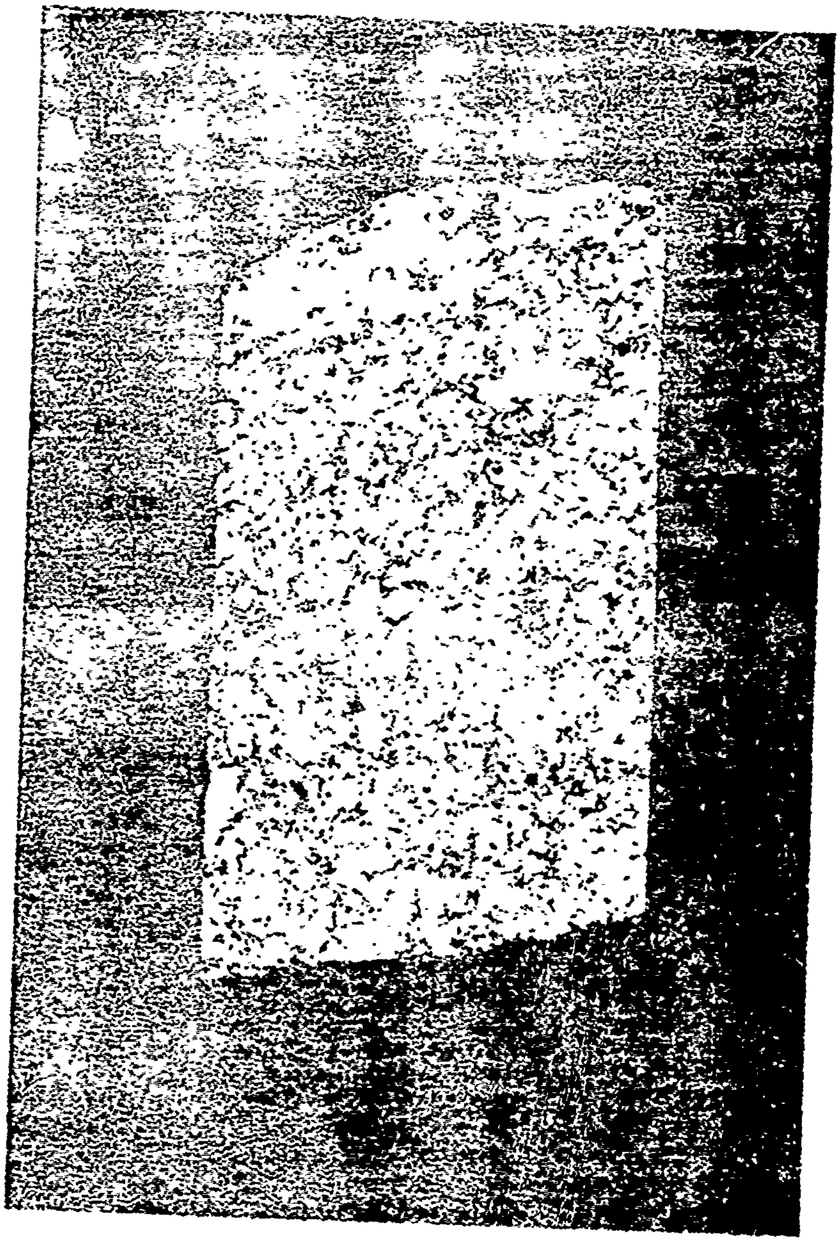
* Shand, S. J., <u>Eruptive Rocks</u>, 3d edition, John Wiley and Sons, New York, N. Y., 1947.



Photograph 1. Sawed surface of piece 9 from core hole CR-4, depth [illegible].7 ft, natural size.

...8. The decrease in the amount of pinkish potash feldspar is also ...onsible for the color change from pink to gray. The difference in ... does not necessarily mean that the physical properties of the gray and the pink rock are different. They may or may not differ; the ...ical tests will determine this.

9. The results of comparing the present sample with the previous ... from core hole CR-42 are listed below:

a. Texture. The present sample is finer grained. The ...imum size of the feldspar phenocrysts is about 1/4 in. as compared ... about 1/2 in. for the rock from hole CR-42.

b. Composition. Both samples contain quartz and feldspars. ...e present sample contains biotite mica and chlorite while the rock ... hole CR-42 contains hornblende and montmorillonitic clay. The ...resent sample contains less potassium feldspar.

c. Physical condition. There are more steeply dipping old ...ctures in the core from hole CR-42 than in this core. More of the ...rioclase crystals show alteration in this rock than in the rock from ...le CR-42. Both cores contain rock that appears fresh and rock that ...ears to be weathered.

...midt number, specific gravity, porosity, and tensile strength

10. Three specimens from each depth interval were selected for the ...sic tests. Results are given below:

[illegible]	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
		Sample A - 30-ft Depth			
[illegible]	55.4	4.11	2.637	0.0	1400
[illegible]	56.1	3.59	2.633	0.0	990
[illegible]	49.0	5.48	2.627	0.0	970
[illegible]	53.5	4.39	2.632	0.0	1120
		Sample B - 60-ft Depth			
[illegible]	56.2	4.54	2.681	0.0	1210
[illegible]	54.8	4.92	2.687	0.0	1460
[illegible]	56.6	5.09	2.692	0.0	1340
[illegible]	55.9	4.85	2.687	0.0	1340

(Continued)

Warren Siting Area: Core No. 3 (Hole CR-4); Series I Tests

(Continued)

Core	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
		Sample C - 180-ft Depth			
13b	57.6	3.35	2.680	0.0	1550
14b	57.9	4.09	2.708	0.0	1360
15c	56.0	5.54	2.599	0.0	1350
Avg	57.2	3.99	2.696	0.0	1420

The results, with the exception of the porosity tests, indicate that the rock in the upper elevations (30 ft) is somewhat less competent than that tested from the other elevations. There is very little difference in the materials from the 60- and 180-ft depths.

Shear tests

11. Direct, single plane shear tests were conducted on three samples from the 60-ft depth interval. Shear strengths of 2030, 1970, and 2100 psi were obtained on samples 7a, 8a, and 8b, respectively. The average strength was 2030 psi. Posttest photographs are given in plate 1.

Unconfined compressive tests

12. Conventional unconfined compressive tests were conducted on specimens from the upper and lower depth intervals and cyclic compressive tests on specimens from the middle depth interval. Results are given below:

Core No.	Depth, ft	Unconfined Compressive Strength, psi
2a	22	22,200
3b	27	25,000
6a	34	25,700
Avg	28	24,300
10a	67	32,800
11a	68	30,100
12a	69	26,600
Avg	68	29,830

(Continued)

(Continued)

Core No.	Depth, ft	Unconfined Compressive Strength, psi
13a	181	32,300
14a	182	31,900
15a	183	32,000
Avg	182	32,070

[illegible], the material from the upper elevation proved to be less competent [illegible] that from the lower elevations.

13. Stress-strain curves for the unconfined compressive tests are [illegible] in plates 2 through 10. The axial (vertical) stress-strain relation[illegible] is virtually linear for most specimens; the hysteresis loops were [illegible] and closed. A posttest photograph of the test specimens, plate 11, [illegible] the nature of failure, steep sided coning.

[illegible] of deformation

14. Young's modulus, shear modulus, bulk modulus, and Poisson's [illegible] were computed on three samples by the dynamic (fundamental [illegible]) method and on the unconfined compressive strength specimens [illegible]cally at approximately 50 percent of the ultimate strength. Results [illegible] given below:

[illegible]	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
[illegible]	5.68	2.71	2.10	0.05
[illegible]	9.59	4.14	4.70	0.16
[illegible]	10.49	4.49	5.30	0.17
		Statically		
[illegible]	9.10	3.78	5.23	0.21
[illegible]	10.50	4.41	5.65	0.19
[illegible]	10.40	4.13	7.22	0.26
[illegible]	10.80	4.50	6.00	0.20
[illegible]	10.40	4.30	5.98	0.21
[illegible]	10.50	4.13	7.61	0.27
[illegible]	10.70	4.18	8.11	0.28
[illegible]	10.80	4.39	6.67	0.23
[illegible]	10.60	4.11	8.41	0.29
[illegible] Static	10.40	4.21	6.76	0.24

Warren Siting Area: Core No. 3 (Hole CR-4): Series I Tests

Velocity measurements

15. The compressional velocity was determined directly as the sonic propagation velocity, and the shear wave velocity was determined from the torsional frequency obtained in the moduli determinations.

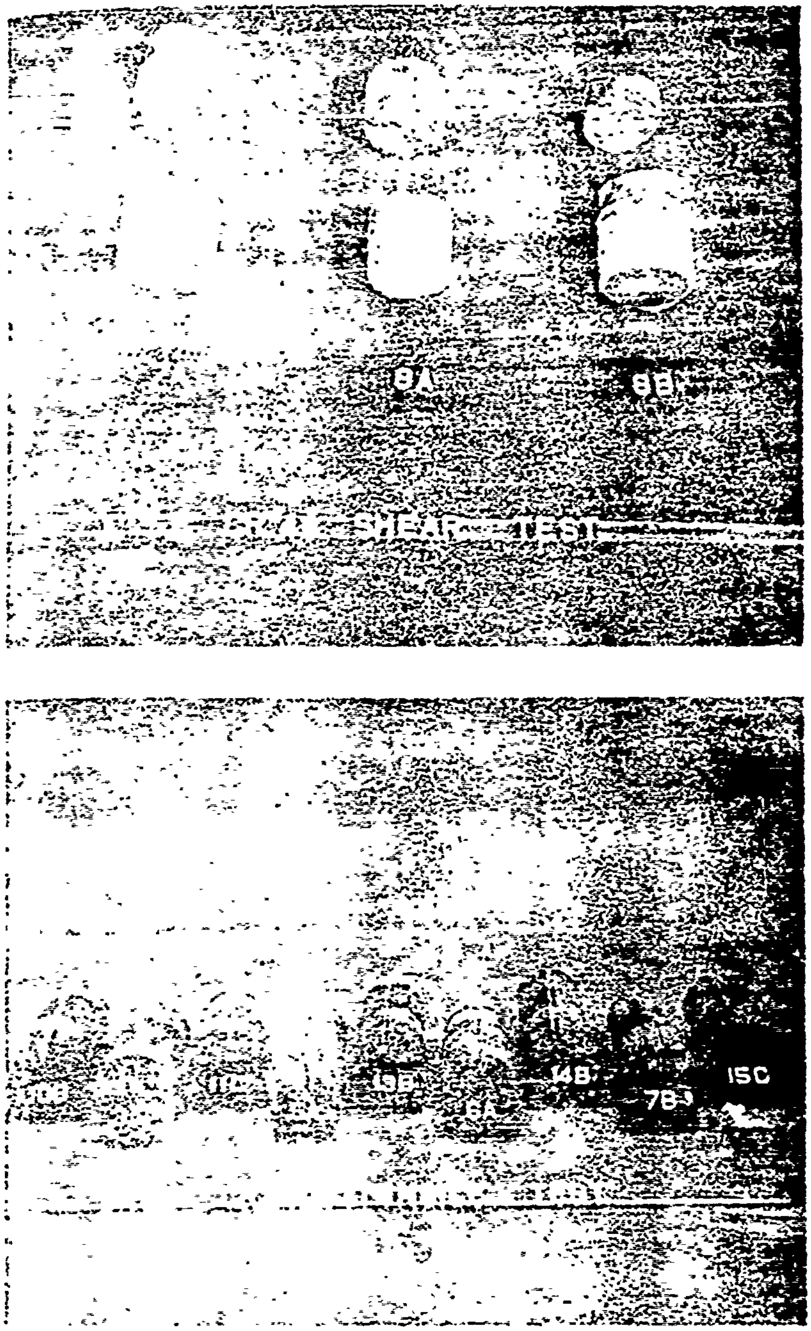
Core No.	Compressional Pulse Velocity, fps	Shear Velocity, fps
2	14,605	8,785
7	17,930	10,045
14	18,795	11,230
Avg	17,110	10,020

The shear velocity is approximately 59 percent of the compressional velocity.

Conclusions

16. The CR-4 core is identified as granite in the upper elevations and tonalite in the lower elevations. The granite is less competent than the tonalite. Consensus results are given below:

Property	Granite	Tonalite
Specific gravity	2.63	2.69
Percent porosity	0.0	0.0
Compressive strength, psi	24,300	30,950
Tensile strength, psi	1,120	1,380
Young's modulus, psi x 10^6	10.0	10.6
Compressional wave velocity, fps	14,605	18,360



Posttest Photographs

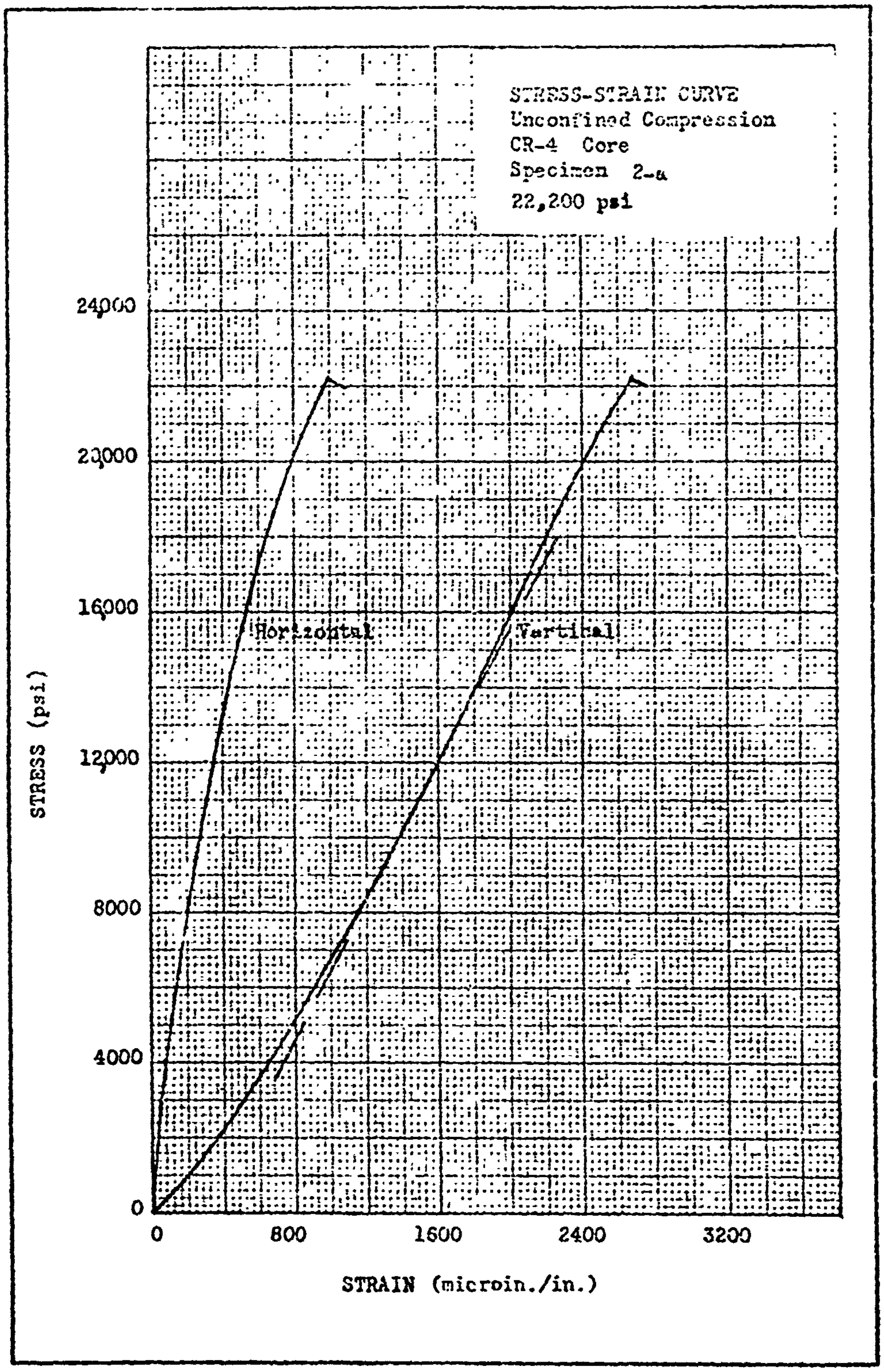

STRESS-STRAIN CURVE
Unconfined Compression
CR-4 Core
Specimen 2-a
22,200 psi
STRESS (psi)
24000
20000
16000
12000
8000
4000
0
Horizontal
Vertical
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 2

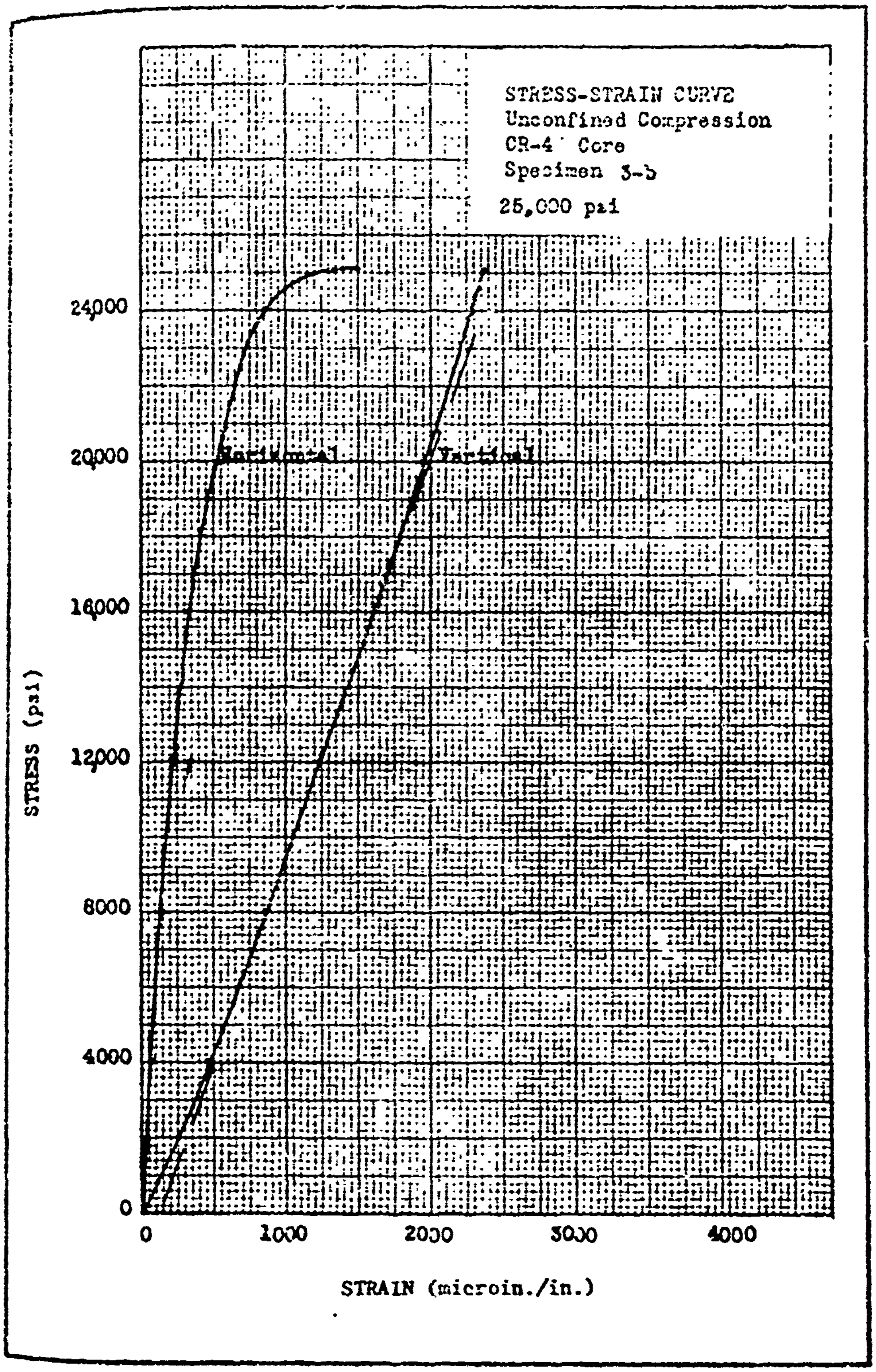

STRESS-STRAIN CURVE
Unconfined Compression
CR-4 Core
Specimen 3-b
25,000 psi
Horizontal
Vertical
24000
20000
16000
12000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 3

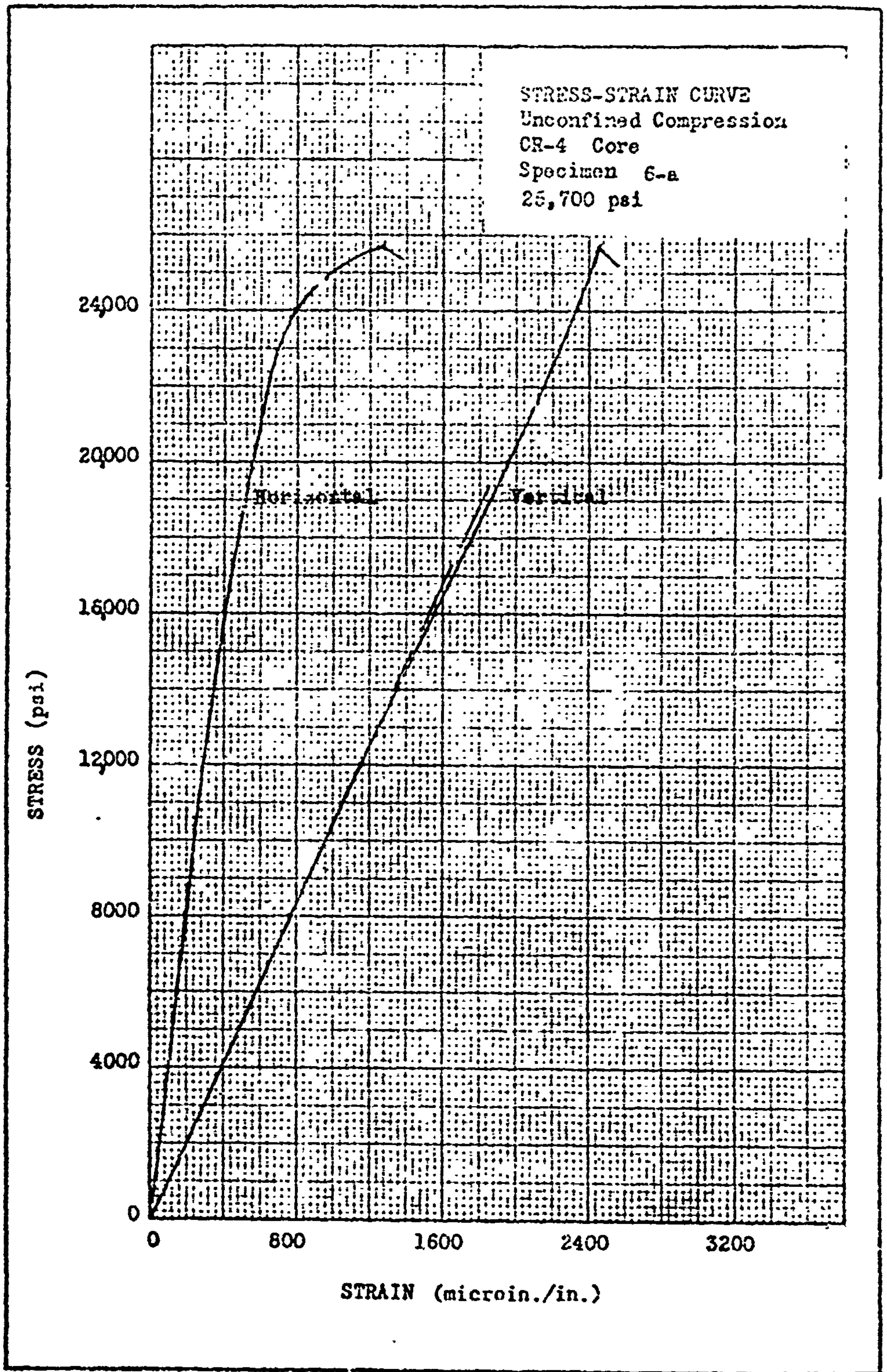

STRESS-STRAIN CURVE
Unconfined Compression
CR-4 Core
Specimen 6-a
25,700 psi
Horizontal
Vertical
STRESS (psi)
24000
20000
16000
12000
8000
4000
0
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 4

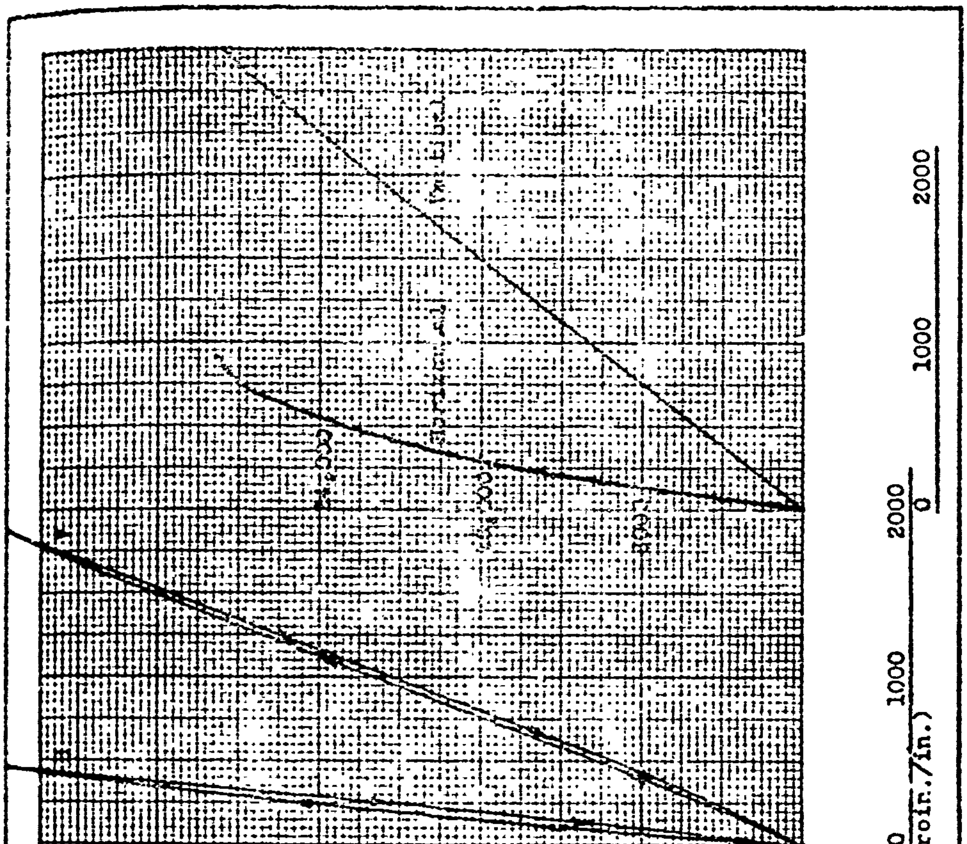

STRESS-STRAIN CURVE
Unconfined Compression
CR- 4 Core
Specimen 10-a
32,800 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
2000

PLATE 5

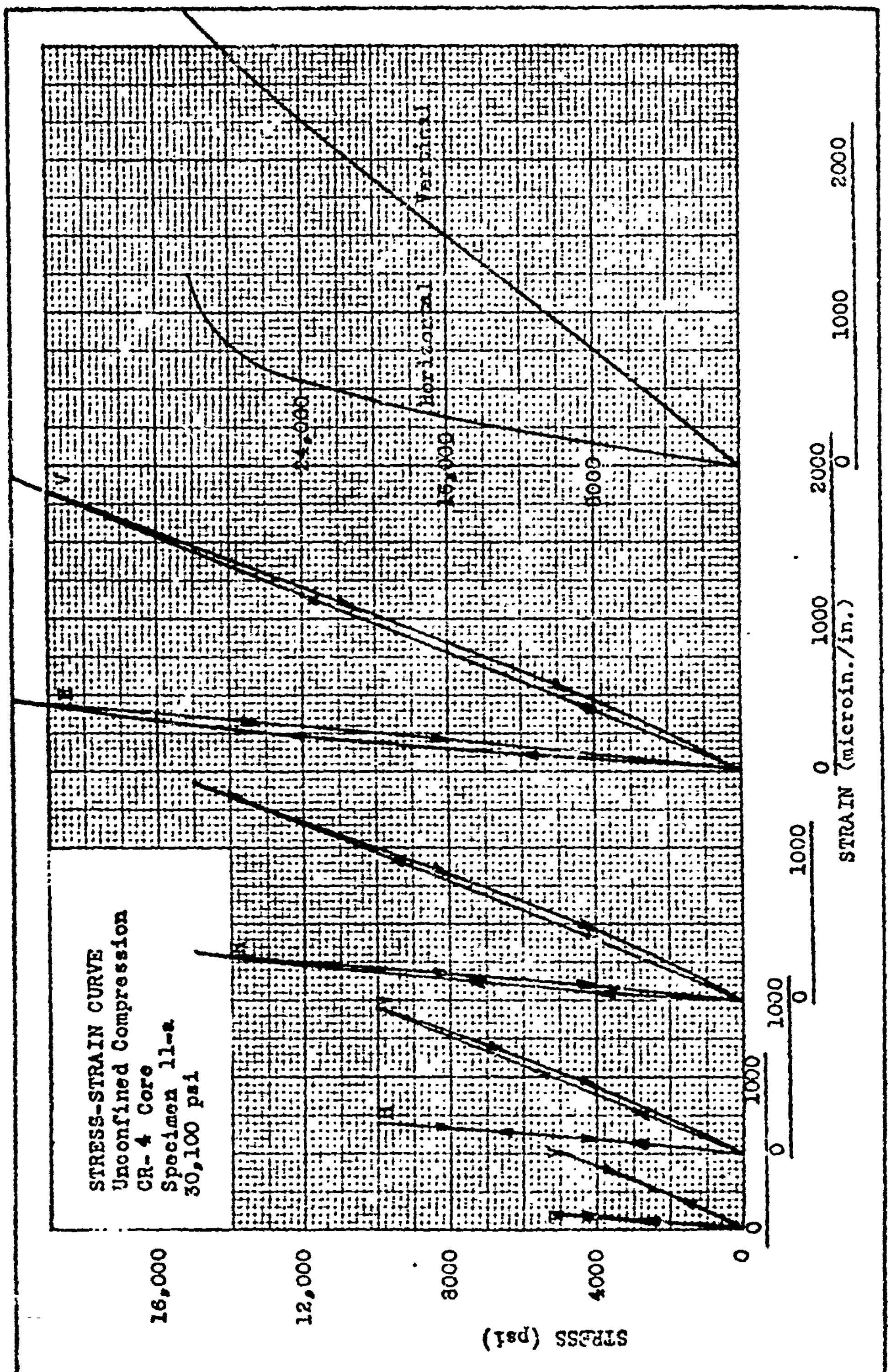

STRESS-STRAIN CURVE
Unconfined Compression
CR- 4 Core
Specimen 11-a
30,100 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
Horizontal
Vertical
24,000
15,000
8000

PLATE 6

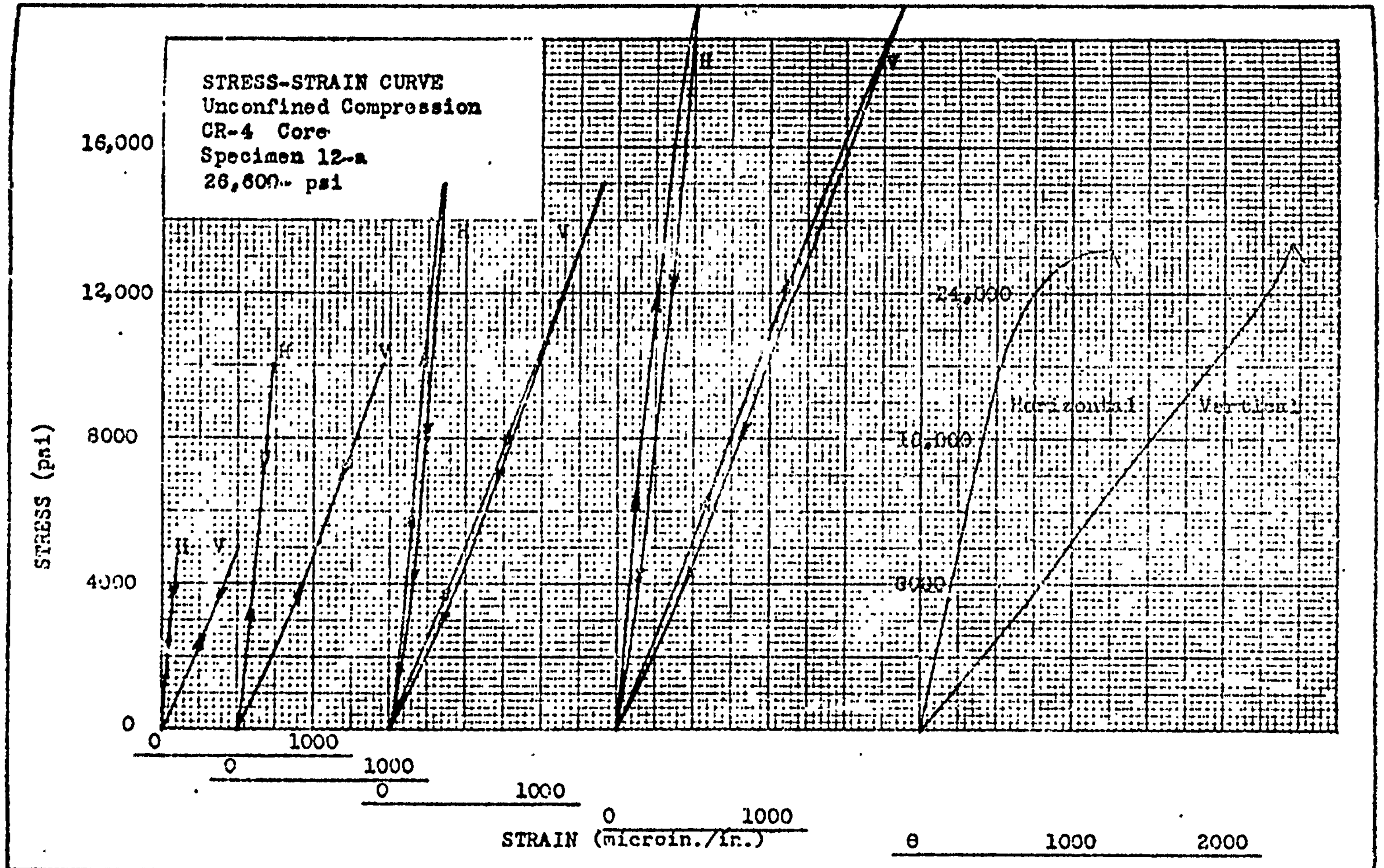

STRESS-STRAIN CURVE
Unconfined Compression
CR-4 Core
Specimen 12-a
26,600 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
Horizontal
Vertical
24,000
16,000
8000
2000
H
V

PLATE 7

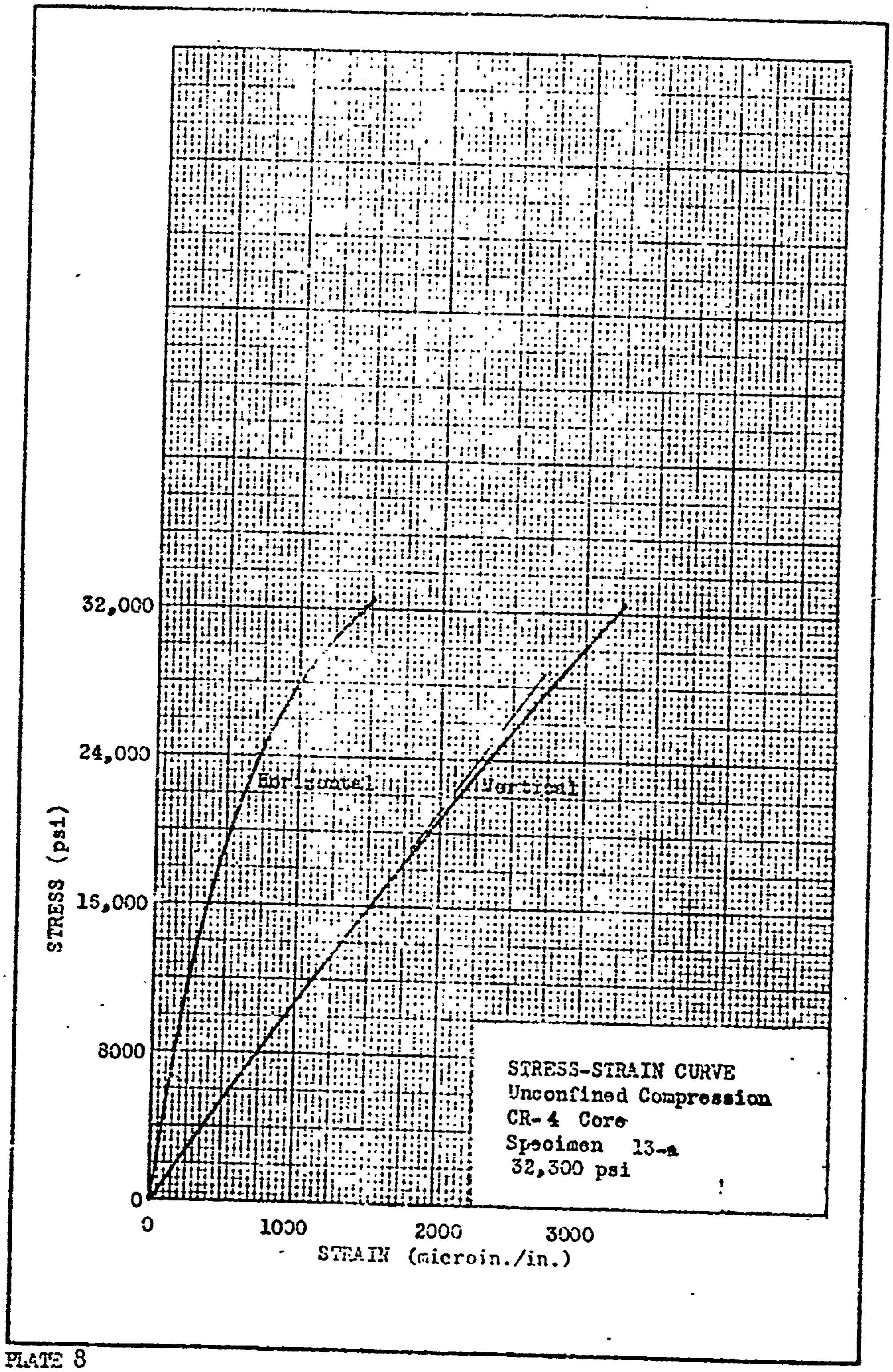

32,000
24,000
16,000
8000
0
STRESS (psi)
Horizontal
Vertical
0
1000
2000
3000
STRAIN (microin./in.)
STRESS-STRAIN CURVE
Unconfined Compression
CR-4 Core
Specimen 13-a
32,300 psi

PLATE 8

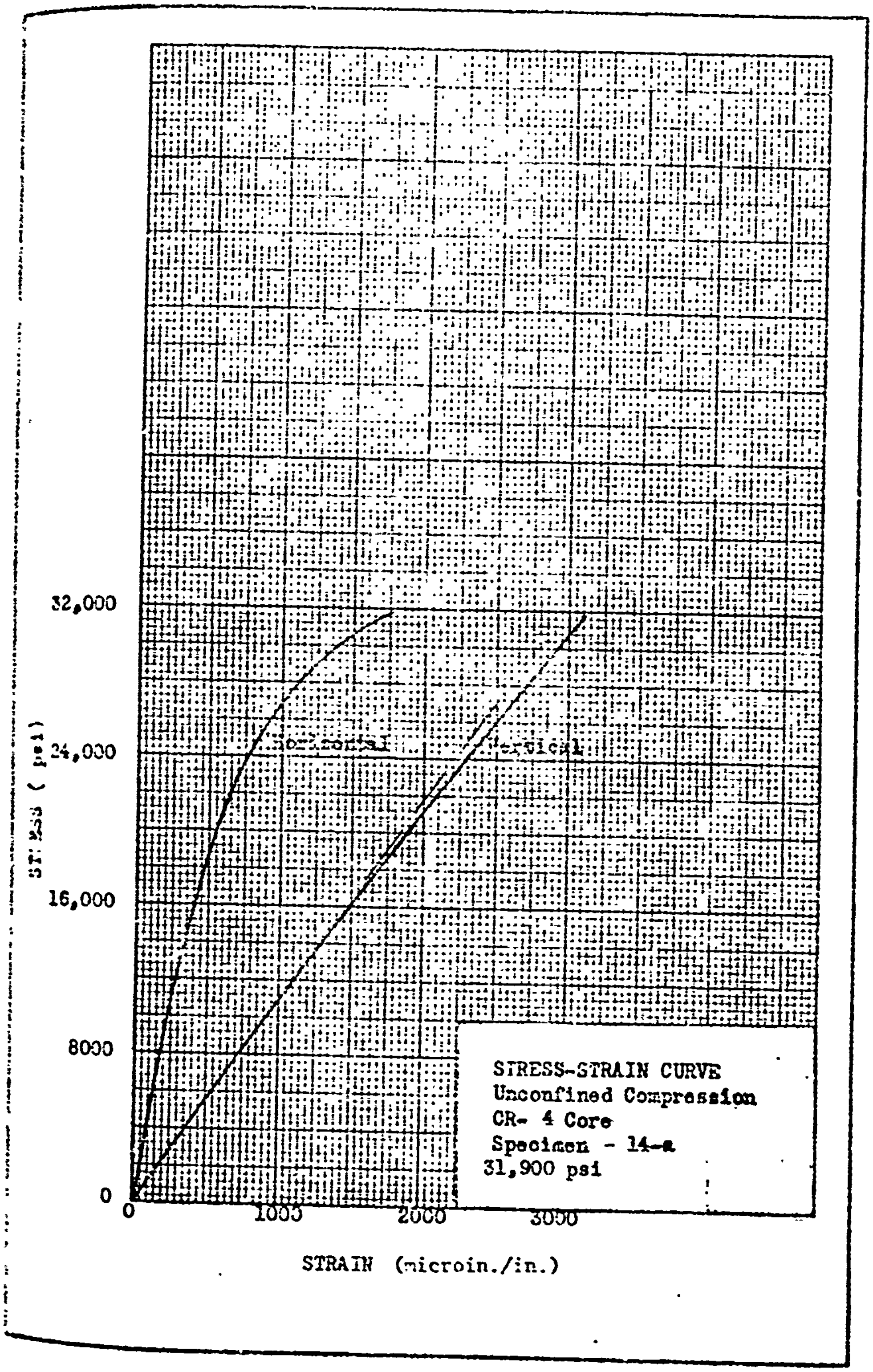

STRESS (psi)
32,000
24,000
16,000
8000
0
0
1000
2000
3000
STRAIN (microin./in.)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR- 4 Core
Specimen - 14-a
31,900 psi

PLATE 9

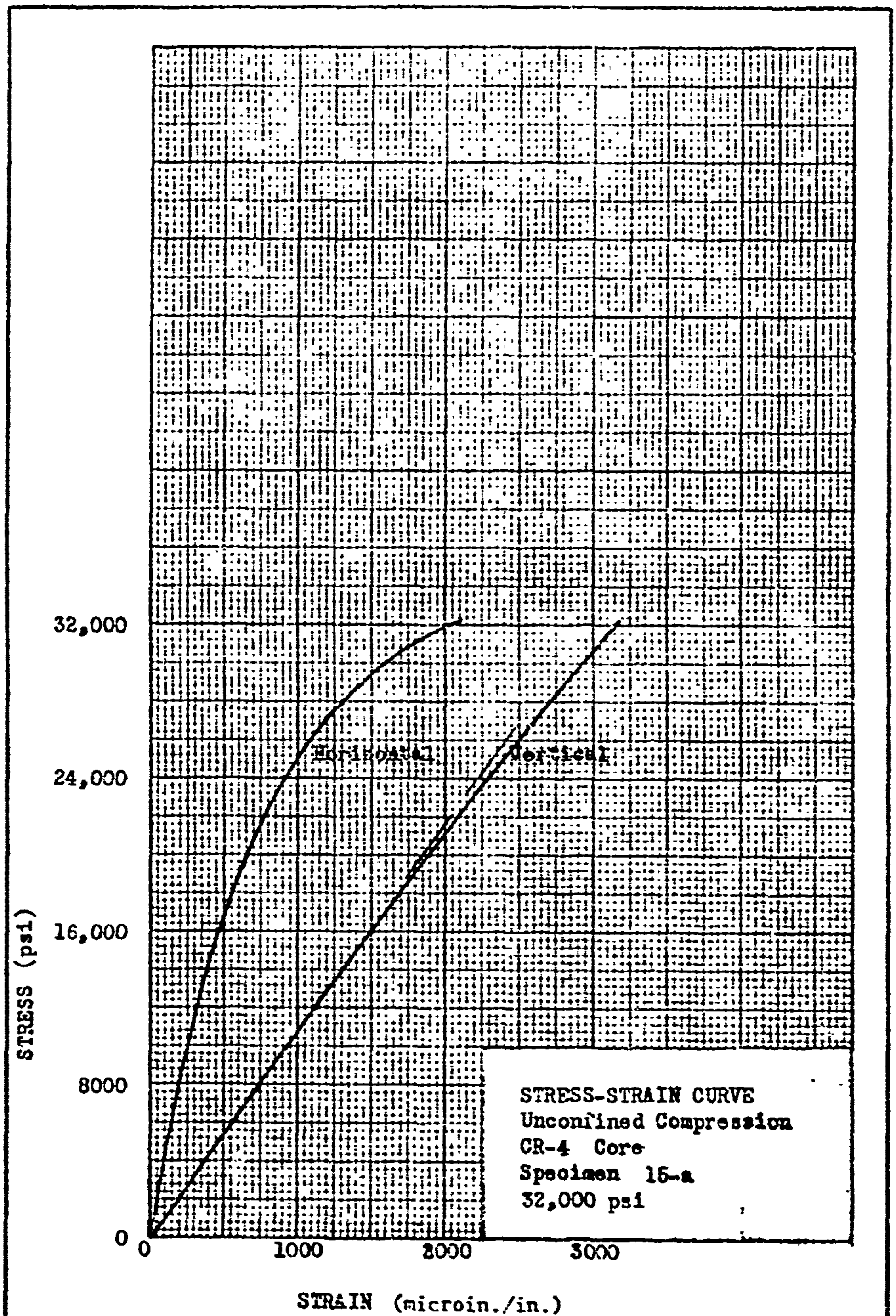
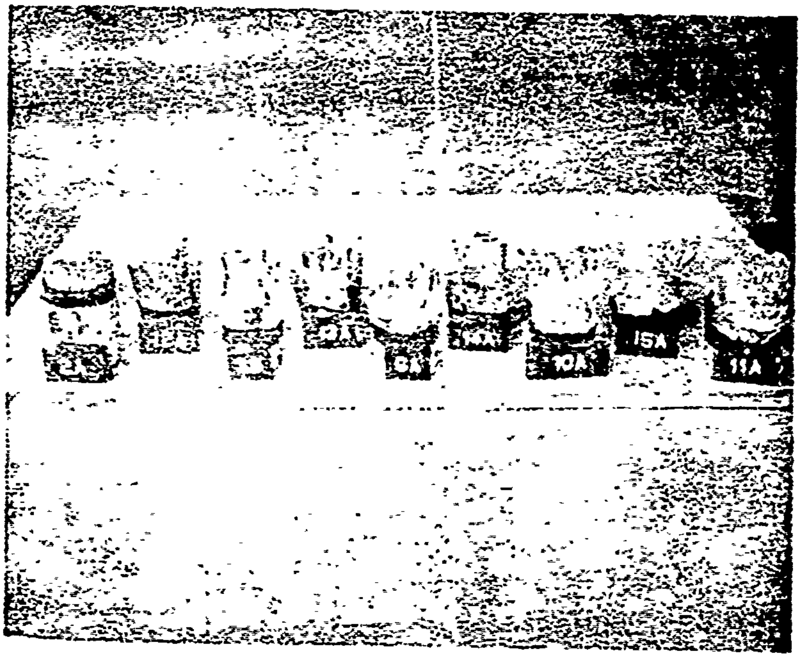

32,000
24,000
16,000
8000
0
STRESS (psi)
0
1000
2000
3000
STRAIN (microin./in.)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR-4 Core
Specimen 15-a
32,000 psi

PLATE 10



Posttest Photograph

APPENDIX F

DATA REPORT - HOLE CR-35 CORES

25 OCTOBER 1968

WARREN SITING AREA

Core No. 9 (Hole CR-35)

1. Eighteen pieces of core from one depth interval were received from the Warren area on 11 October 1968, designated CR-35 core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	17
A	2	17
A	3	18
A	4	19
A	5	20
A	6	21
A	7	22
A	8	23
A	9	24
A	10	25
A	11	26
A	12	26
A	13	27
A	14	28
A	15	29
A	16	29
A	17	29
A	18	30

2. The hole from which the core was taken was located in Albany County, Wyoming, township 15N, range 71W, section 2.

Warren Siting Area: Core No. 9 (Hole CR-35); Series I Tests

Results

Petrographic examination

3. About 13 ft of NX rock core from depths of 17.1 through 30.3 ft in hole CR-35 was received in October 1958 for testing. The petrographic specimen is identified below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-9	15	28	1/4

4. All of the pieces of core were similar in appearance except that the bottom portion of piece 16 and the top portion of piece 17 were unusually coarse grained. Most fracture surfaces were fresh and apparently were produced in drilling.

5. The test procedure was the same as that for the other rocks in this series.

6. The rock is coarse-grained, pink granite with white and black patches composed of pink microcline, white plagioclase, colorless quartz, and black biotite with smaller amounts of hornblende, kaolinite, pyroxene, and several other minerals. The plagioclase is either albite or oligoclase. There is some alteration of the feldspars, especially of the plagioclase.

7. The rock in this core is similar to the reddish granites from holes CR-42 and CR-48; all three cores may have been taken in the same igneous body.

8. The size of the pinkish microcline phenocrysts decreased from a maximum over 1 in. in CR-42 to about 3/4 in. in CR-48 to about 1/2 in. in the present core (photograph 1). As the size of the microcline phenocrysts decreased, the white plagioclase phenocrysts increased in size until they reached a maximum size of about 1/2 in. in the present core.

9. If there are significant differences in physical properties between these three cores, they may relate to the textural variations just described.

Schmidt number, specific gravity, porosity, and tensile strength

10. Three specimens were selected for the basic tests. Results are given below:

Photograph 1. Sawed surface of piece 15 from core hole CR-35, depth 28 ft, natural size.

Warren Siting Area: Core No. 9 (Hole CR-35); Series I Tests

Core	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
3c	54.5	2.77	2.666	0.4	955
13b	53.3	3.29	2.596	0.0	990
17b	50.2	2.15	2.598	0.0	660
Avg	52.7	2.74	2.587	0.1	870

Shear tests

11. Direct single plane shear tests conducted on specimens 2a, 7b, and 18a yielded shear strengths of 935, 1080, and 985 psi, respectively. The average, 1000 psi, is somewhat lower than that of the other granite from the Warren area.

Unconfined compressive strength tests

12. Unconfined compressive strength tests were conducted on five specimens, three cyclic tests and two conventional tests. The results, given below, indicate good uniformity of the CR-35 core and comparable strength to the other Warren area granite.

Core No.	Depth, ft	Unconfined Compressive Strength, psi
3a	18	21,300
7a	22	21,700
10a	25	21,740
14a	28	21,360
17a	29	23,700
Avg	24	21,960

13. Specimens 3a, 7a, and 17a had two vertical and two horizontal electrical resistance gages affixed in order to monitor strain during loading. Unloading cycles were made at 5000-psi intervals up to 15,000 psi. Stress-strain curves are given in plates 2, 3, and 4. The hysteresis loops were small and closed. The peculiar shape of the third cycle curve on specimen 17a is unexplained. Possibly the strain gage loosened during loading. A posttest photograph of the test specimens, plate 5, shows the nature of failure, steep sided coning.

Moduli of deformation

14. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on three samples by the dynamic (fundamental

frequency) method and on three unconfined compressive strength specimens statically at approximately 50 percent of the ultimate strength. Results are given below:

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
9	4.78	1.93	3.06	0.24
		Statically		
3a	7.80	3.28	4.19	0.19
7a	7.90	3.24	4.70	0.22
17a	8.10	3.24	5.40	0.25
Avg Static	7.93	3.25	4.76	0.22

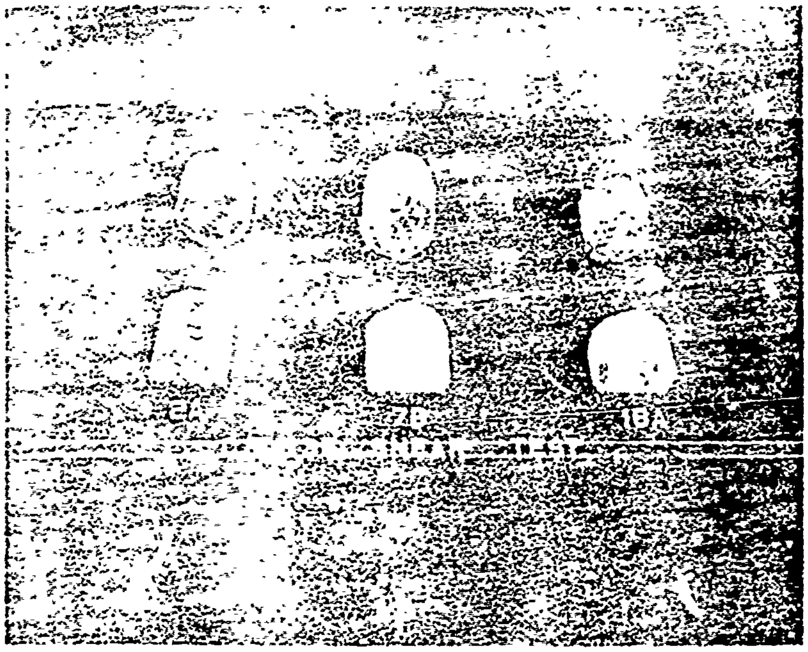
Velocity measurements

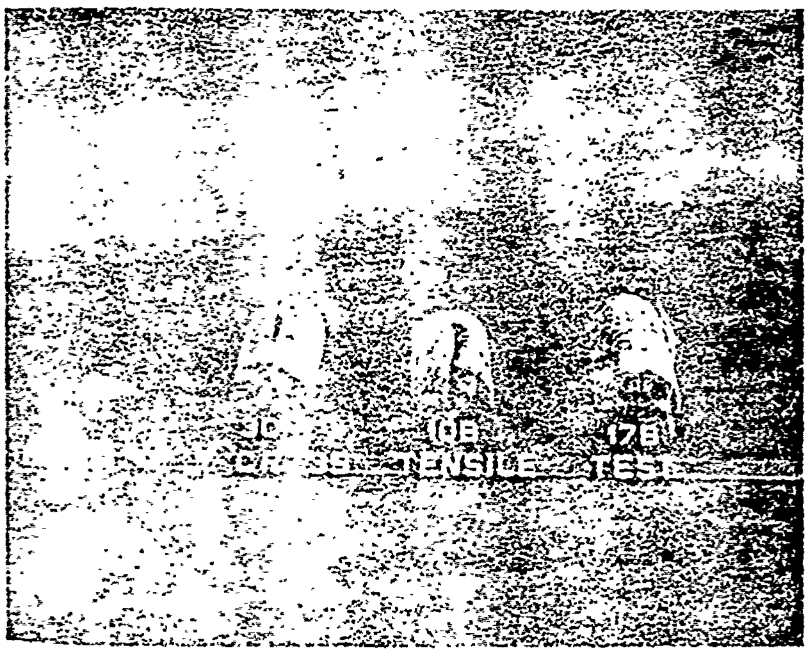
15. The compressional wave velocity was determined directly as the sonic propagation velocity on specimen No. 9 to be 12,545 fps. The shear wave velocity was determined from the torsional frequency obtained in the moduli determinations to be 7350 fps.

Conclusions

16. The CR-35 core is identified as a coarse-grained, pink granite similar to the rock from holes CR-42 and CR-48. Consensus results of physical properties are:

Property	Result
Specific gravity	2.69
Percent porosity	0.1
Compressive strength, psi	21,960
Tensile strength, psi	870
Young's modulus, psi x 10^6	7.9
Compressional wave velocity, fps	12,545





Posttest Photographs

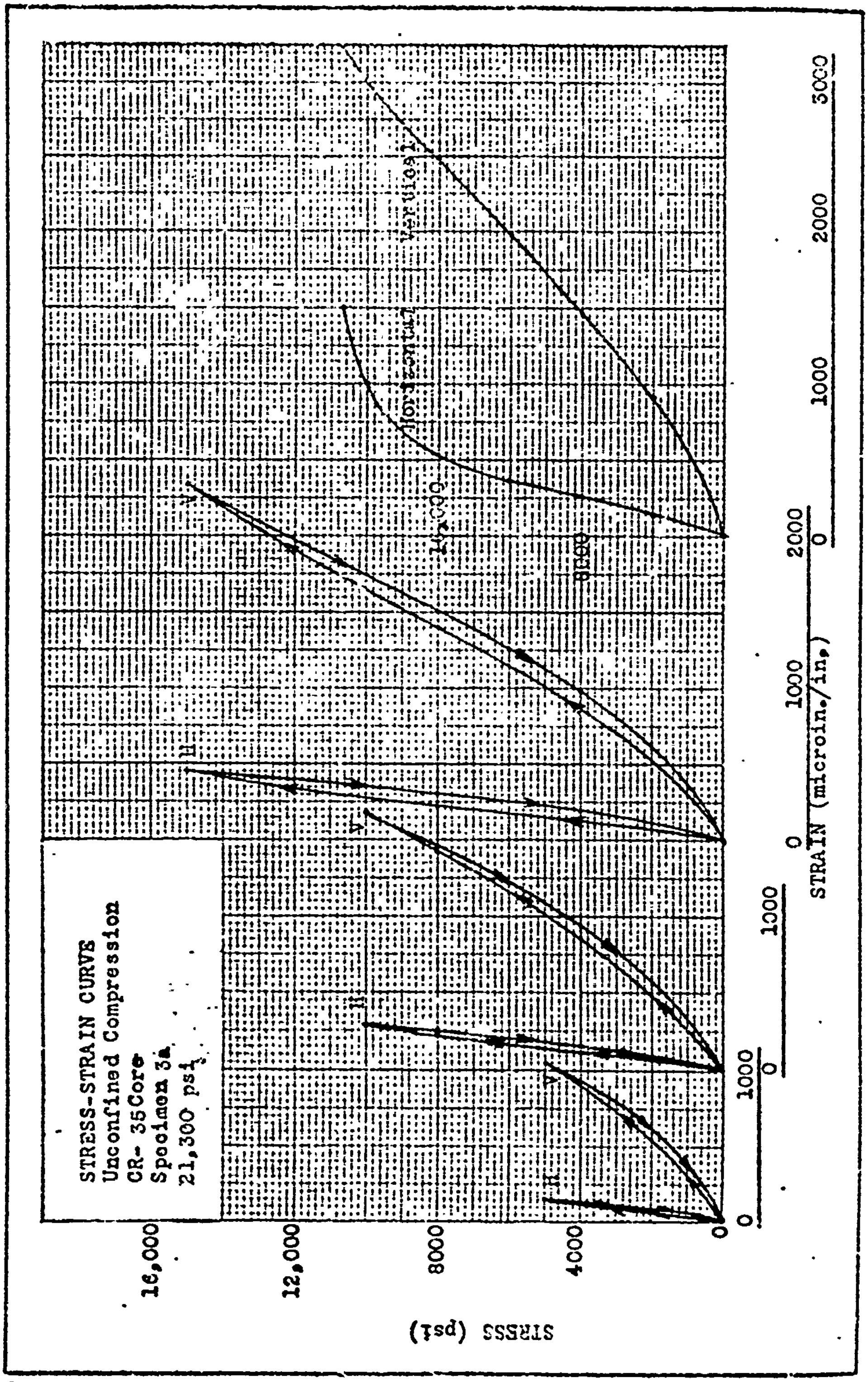

STRESS-STRAIN CURVE
Unconfined Compression
CR- 35Core
Specimen 3a
21,300 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
2000
3000
Horizontal
Vertical
H
V

PLATE 2

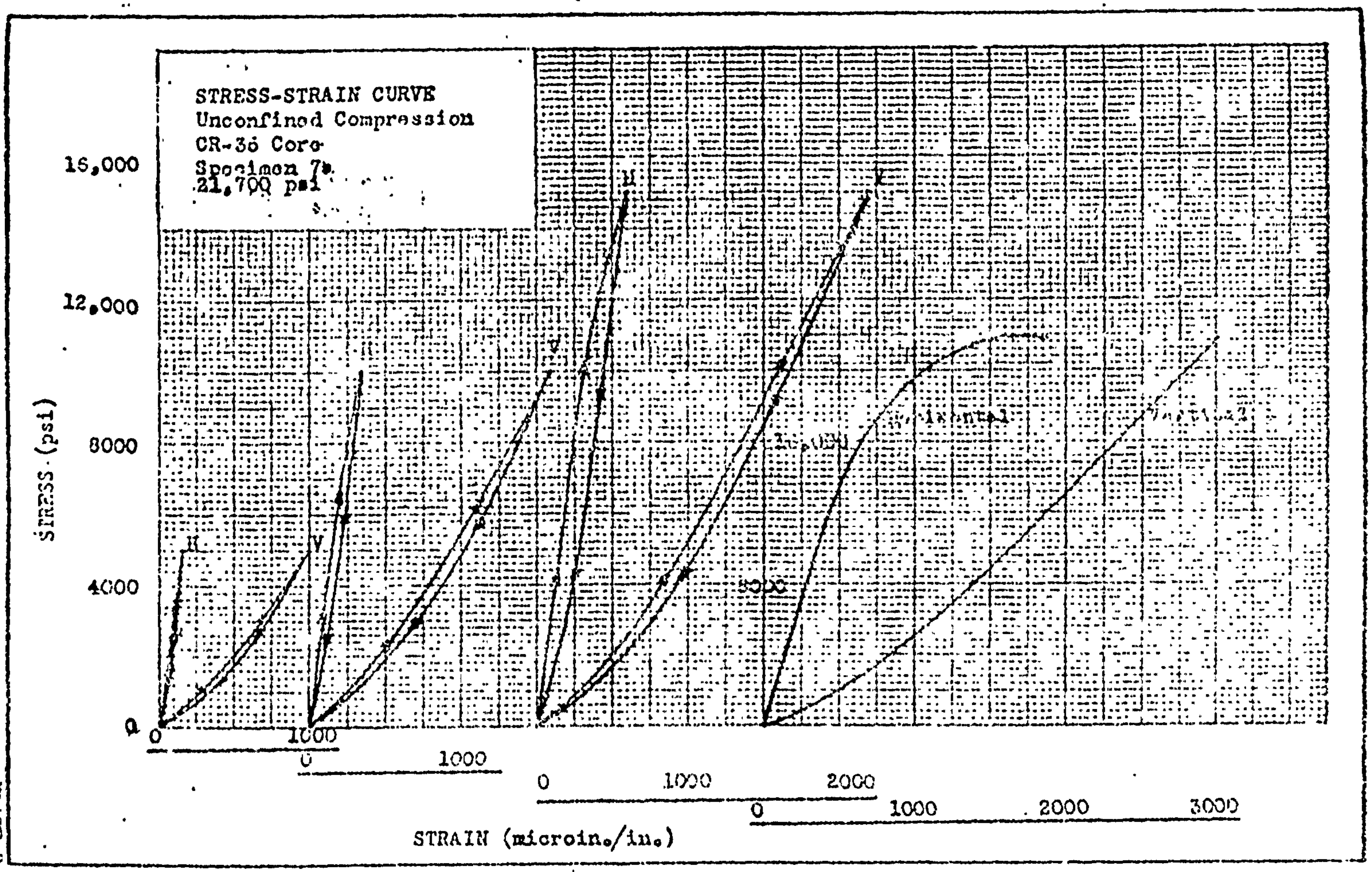

STRESS-STRAIN CURVE
Unconfined Compression
CR-36 Core
Specimen 7a
21,700 psi
16,000
12,000
8000
4000
0
H
V
Horizontal
Vertical
STRESS (psi)
STRAIN (microin./in.)
1000
2000
3000

PLATE 3

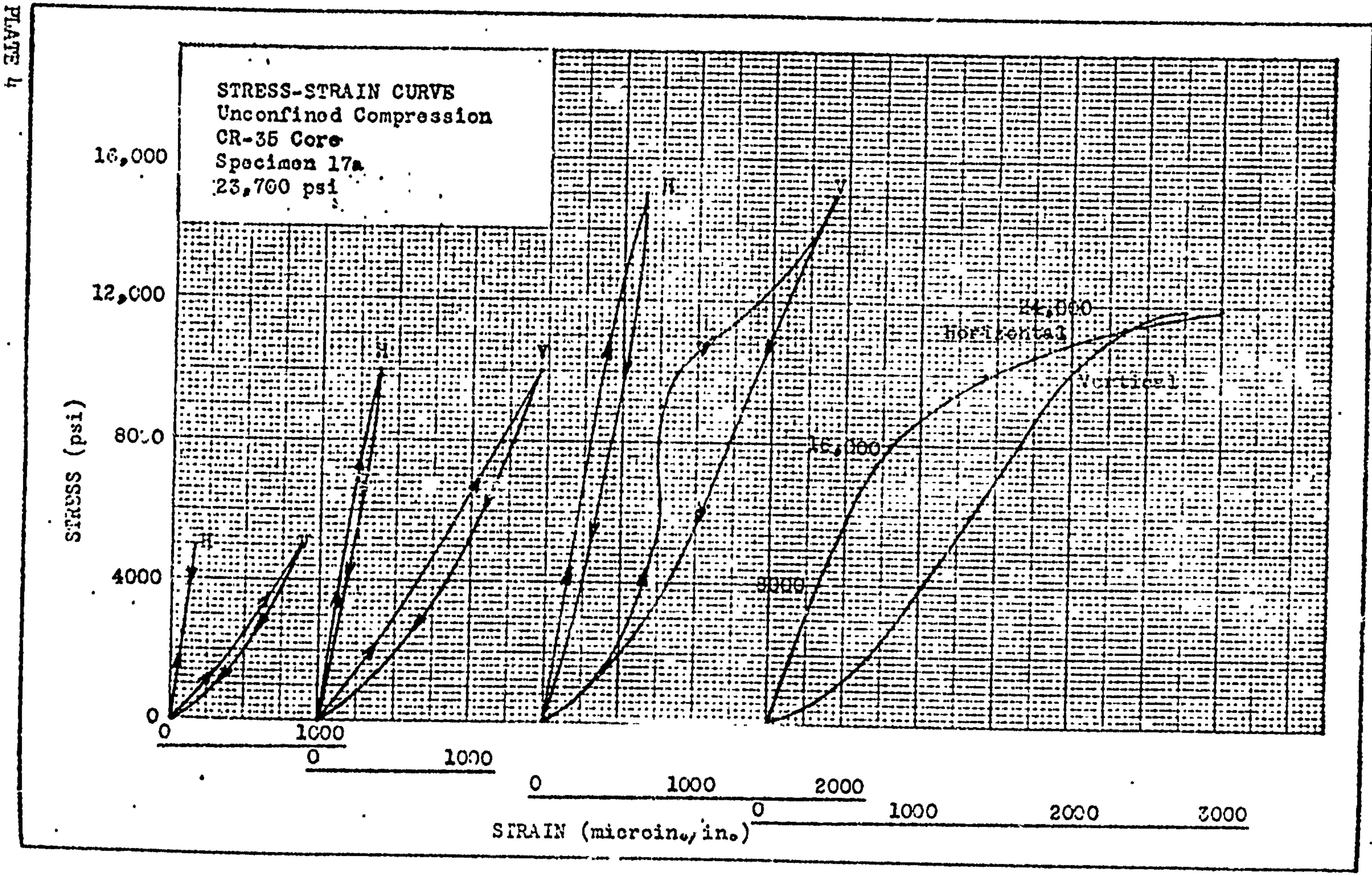
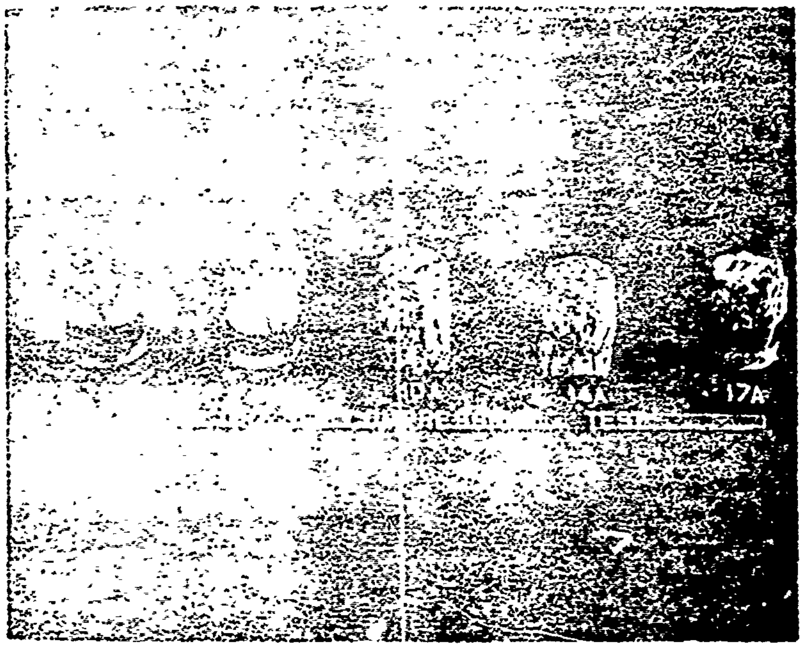

STRESS-STRAIN CURVE
Unconfined Compression
CR-35 Core
Specimen 17a
23,700 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
2000
3000
H
V
14,000
Horizontal
Vertical
8000

PLATE 4



Posttest Photograph

PLATE 5

APPENDIX G

DATA REPORT - HOLE CR-39 CORES

21 OCTOBER 1968

WARREN SITING AREA

Core No. 6 (Hole CR-39)

1. Fourteen pieces of core were received from the Warren area on 7 October 1958, designated CR-39 core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	55
A	2	57
A	3	58
A	4	59
A	5	50
B	6	144
B	7	145
B	8	146
B	9	147
C	10	192
C	11	193
C	12	195
C	13	196
C	14	197

2. The hole from which the core was taken was located in Albany County, Wyoming, township 14N, range 71W, section 23.

Warren Siting Area: Core No. 5 (Hole CR-39): Series I Tests

Results

Petrographic examination

3. About 15 ft of NX rock core from three depths in hole CR-39 in Albany County, Wyoming, were received on 7 October 1968 for testing. The petrographic specimens are identified below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-7	6 (bottom portion)	144	1/3
SAMSO-2 DC-7	12 (bottom portion)	195.3	1/3

4. All of the pieces of core were similar in appearance and no pre-existing fracture surfaces were seen. The petrographic work was similar to that done for all of the previous rocks in this test series.

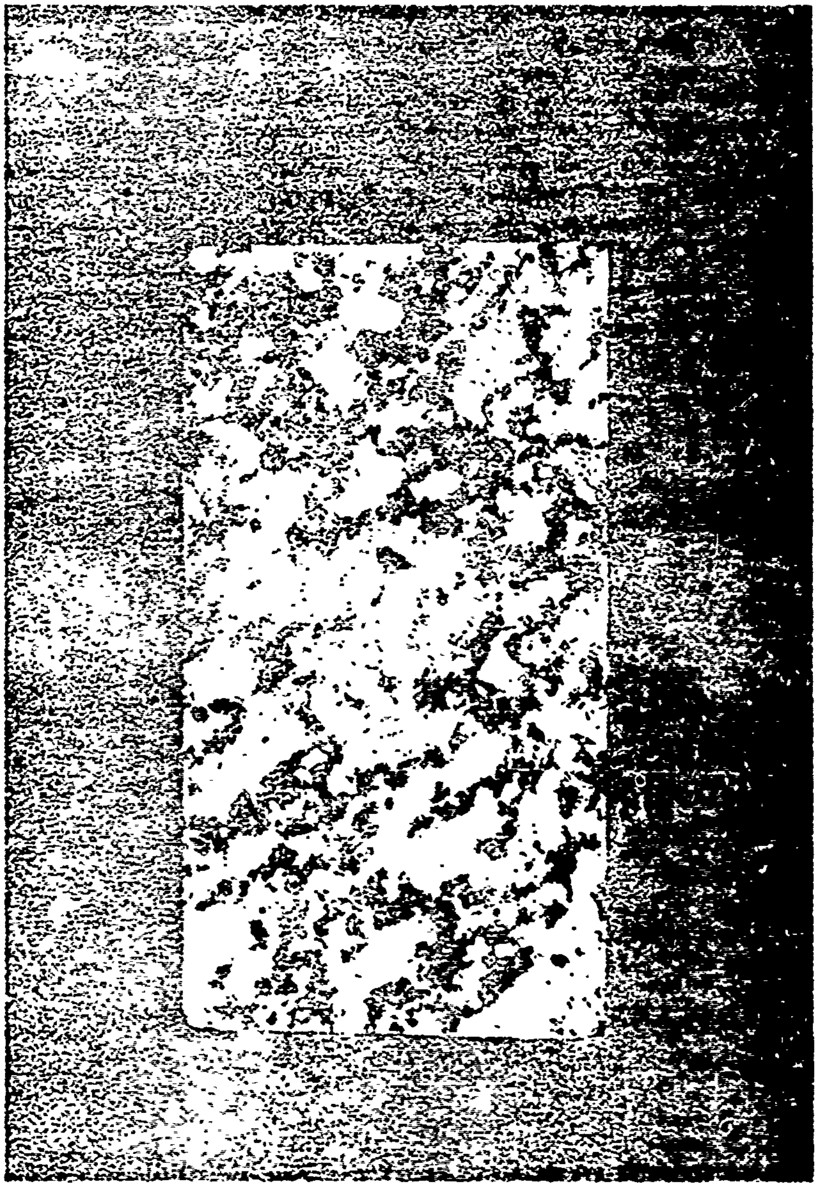
5. The core is composed of coarse-grained, light-colored grayish rock which was logged as granite. The petrographic data indicate granite is a suitable name.

6. The rock is composed largely of quartz, potassium feldspar, plagioclase feldspar (probably oligoclase), and biotite with a lesser amount of hornblende and a little kaolinite. The appearance of the rock is shown by photograph 1.

7. This core was compared with the core from hole CR-42 since both were coarse-grained granites. The results of this comparison are shown below.

Core from Hole CR-39	Core from Hole CR-42
Coarse-grained light-colored granite	Coarse-grained reddish granite
All breaks in core appear to be fresh.	Old limonite coated fractures are numerous.
Abundant biotite.	Practically no biotite
No montmorillonitic clay	Some montmorillonitic clay
-	More quartz in this core

Warren Siting Area: Core No. [illegible] (Hole CR-39); Series I Tests



Photograph 1. Sawed surface of piece 6 from core hole CR-39, depth 144 ft. Slightly larger than natural size.

8. The presence of the montmorillonitic clay and the old fracture ...aces in the core from hole CR-42 indicates that there has been more ...ation of this rock and that it is more broken. The presence of ...existing fracture systems in the rock from core hole CR-42 may well ... the only difference of any importance between the cores from the two ...es.

...dt number, specific gravity, porosity, and tensile strength

9. Three specimens from each depth interval were selected for the ...dt test. However, due to the apparent uniform nature of the rock, ... the three samples from the middle interval were subjected to all ...ests. Results are given below:

...ce	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
		Sample A - 50-ft Depth			
...a	52.1	3.32	2.706	-	-
...a	53.4	3.11	2.711	-	-
...a	54.5	3.66	2.717	-	-
...ge	53.3	3.36	2.711		
		Sample B - 145-ft Depth			
...a	52.5	3.08	2.718	0.8	775
...a	51.2	2.90	2.712	0.7	845
...a	49.9	2.78	2.708	0.4	825
...ge	51.2	2.92	2.713	0.6	815
		Sample C - 195-ft Depth			
...a	52.0	2.65	2.720	-	-
...a	52.8	3.38	2.705	-	-
...a	51.8	2.84	2.712	-	-
...ge	52.2	2.96	2.712		

...ications are that the CR-39 core is a hard, uniform material through-...t the depths sampled.

...ear tests

10. Direct single plane shear tests were conducted on one specimen ...m each of the three depth intervals as indicated:

Warren Siting Area: Core No. 6 (Hole CR-39); Series I Tests

Specimen No.	Depth, ft	Shear Strength, psi
4b	59	1340
6b	44	1305
12a	195	1460
Avg	-	1370

Unconfined compressive strength tests

11. Conventional unconfined compressive strength tests were conducted on specimens from the upper and lower depth intervals and cyclic compressive tests on specimens from the middle depth interval. The results, given below, again indicate the uniform nature of the CR-39 core.

Core No.	Depth, ft	Unconfined Compressive Strength, psi
2a	57	21,860
3b	58	21,200
4b	59	20,260
Avg	58	21,100
7b	145	20,400
8b	146	21,000
9a	147	20,000
Avg	146	20,470
10a	192	20,480
11a	193	21,770
13a	196	21,510
Avg	194	21,250

12. The specimens from the middle depth interval had two vertical and two horizontal electrical resistance gages affixed in order to monitor strain during loading. Unloading cycles were made at 5000-psi intervals up to 15,000 psi. Stress-strain curves are given in plates 2, 3, and 4. The hysteresis loops were small and closed. A posttest photograph of the test specimens, plate 5, shows the nature of failure, steep sided coning.

Warren Siting Area: Core No. 6 (Hole CR-39); Series I Tests

Moduli of deformation

13. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on three samples by the dynamic (fundamental frequency) method and on the unconfined compressive strength specimens statically at approximately 50 percent of the ultimate strength. Results are given below:

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
1	8.86	3.95	3.89	0.12
6	8.38	3.88	3.33	0.08
14	8.06	3.45	3.95	0.16
		Statically		
[illegible]	8.00	3.03	7.41	0.32
[illegible]	7.80	3.12	5.20	0.25
[illegible]	7.90	3.04	6.58	0.30

Velocity measurements

14. The compressional wave velocity was determined directly as the sonic propagation velocity, and the shear wave velocity was determined from the torsional frequency obtained in the moduli determinations.

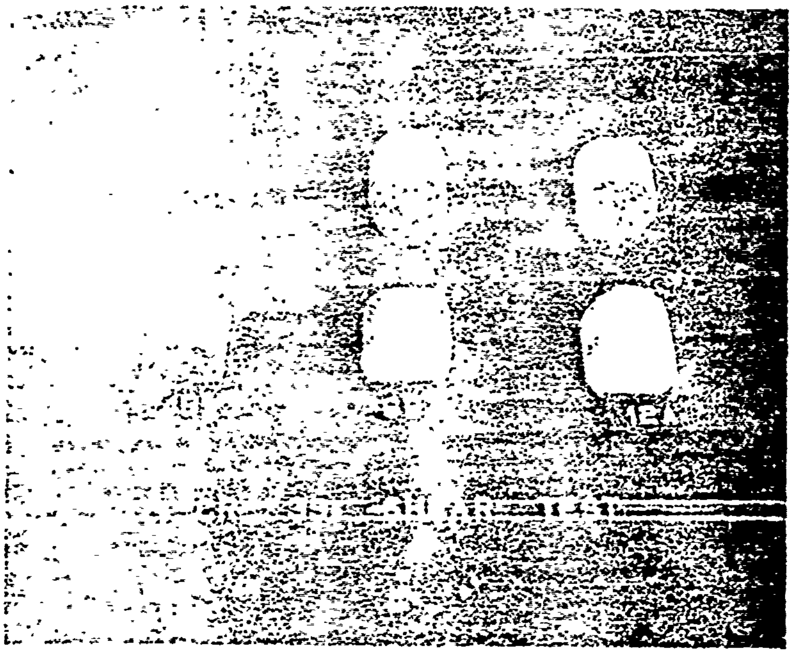
Core No.	Compressional Velocity, fps	Shear Velocity, fps
1	17,360	10,440
6	17,100	10,365
14	16,630	9,755
Avg	17,030	10,185

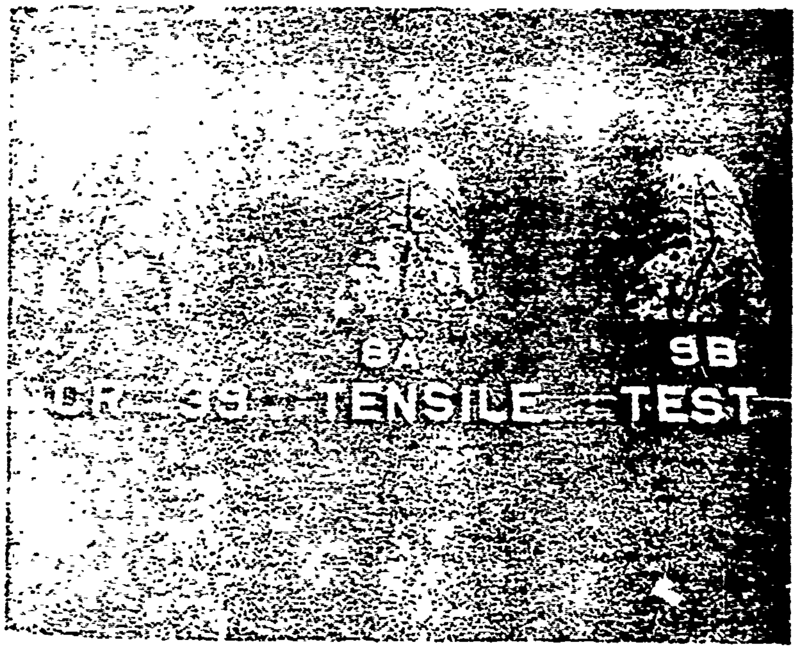
The shear velocity is approximately 60 percent of the compressional velocity.

Conclusions

15. The CR-39 core is identified as a coarse-grained granite somewhat similar to the core from hole CR-42. The core is very uniform in physical properties throughout the samples tested. Consensus results of physical properties are:

Property	Results
Specific gravity	2.71
Percent porosity	0.6
Compressive strength, psi	20,940
Tensile strength, psi	815
Young's modulus, psi x 10^6	8.0
Compressional wave velocity, fps	17,030





Posttest Photographs

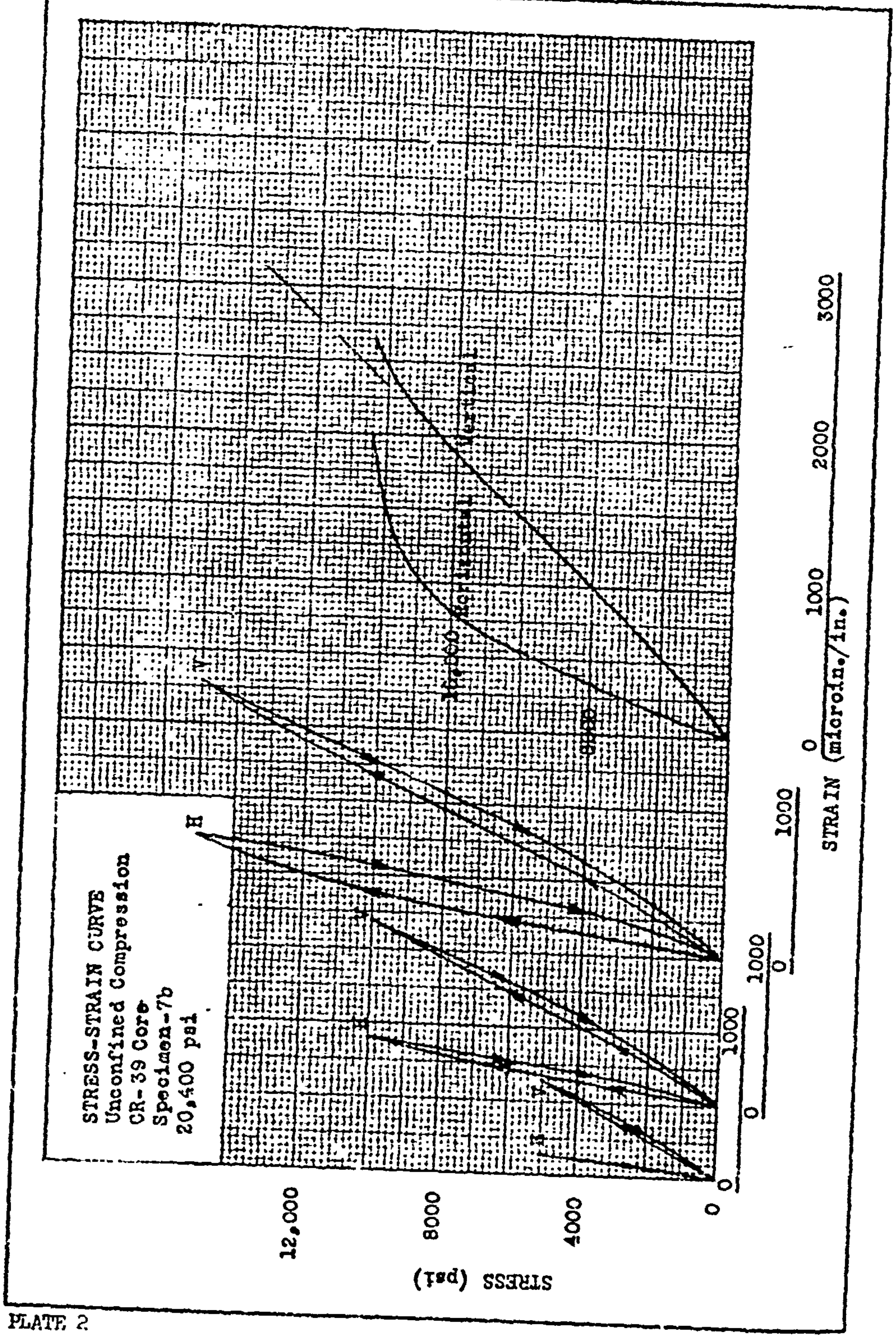

STRESS-STRAIN CURVE
Unconfined Compression
CR-39 Core
Specimen-7b
20,400 psi
STRESS (psi)
0
4000
8000
12,000
STRAIN (microin./in.)
0
1000
2000
3000
H
V

PLATE 2

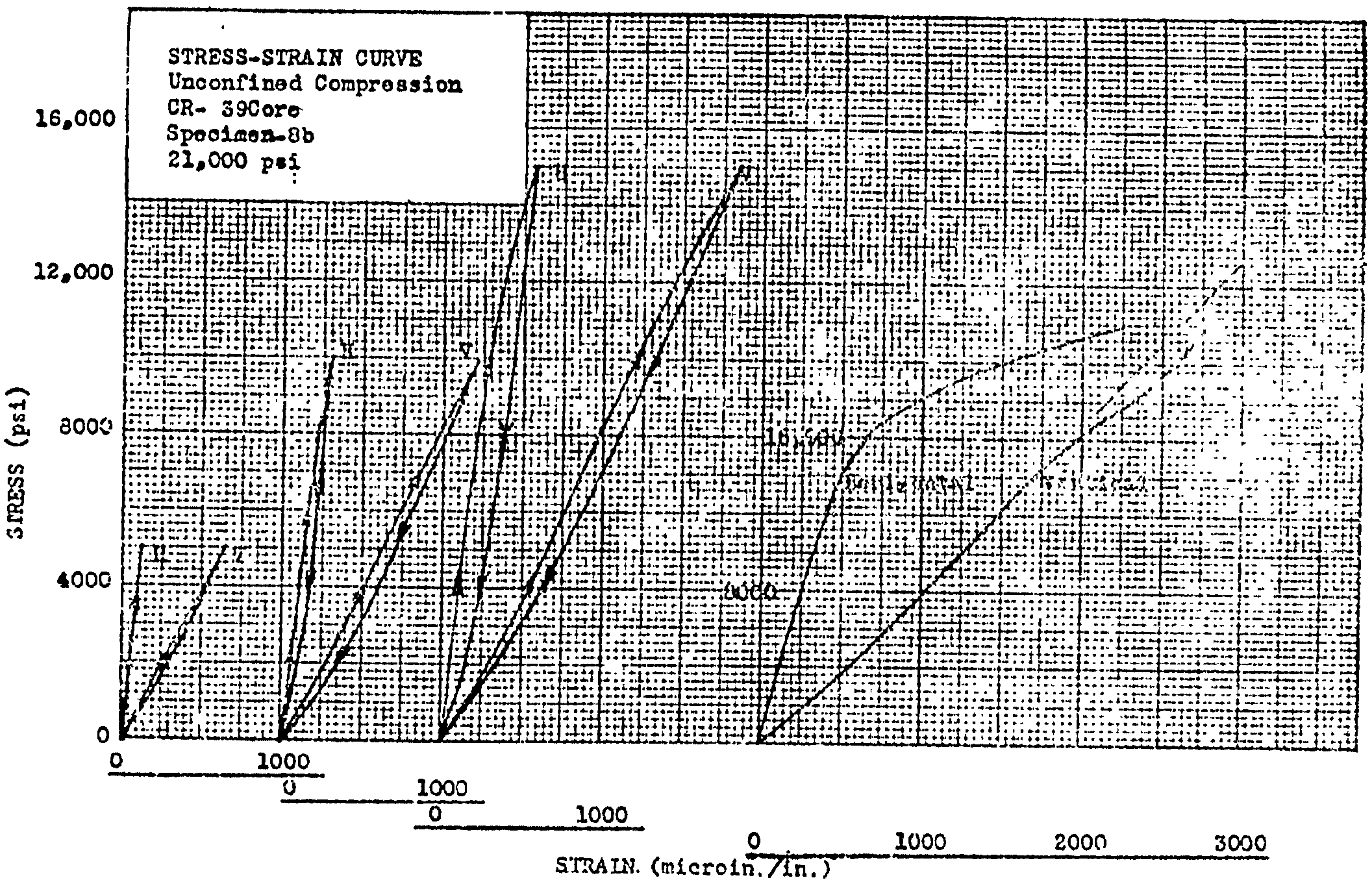

STRESS-STRAIN CURVE
Unconfined Compression
CR- 39Core
Specimen-8b
21,000 psi
STRESS (psi)
16,000
12,000
8000
4000
0
0
1000
0
1000
0
1000
0
1000
2000
3000
STRAIN (microin./in.)

PLATE 3

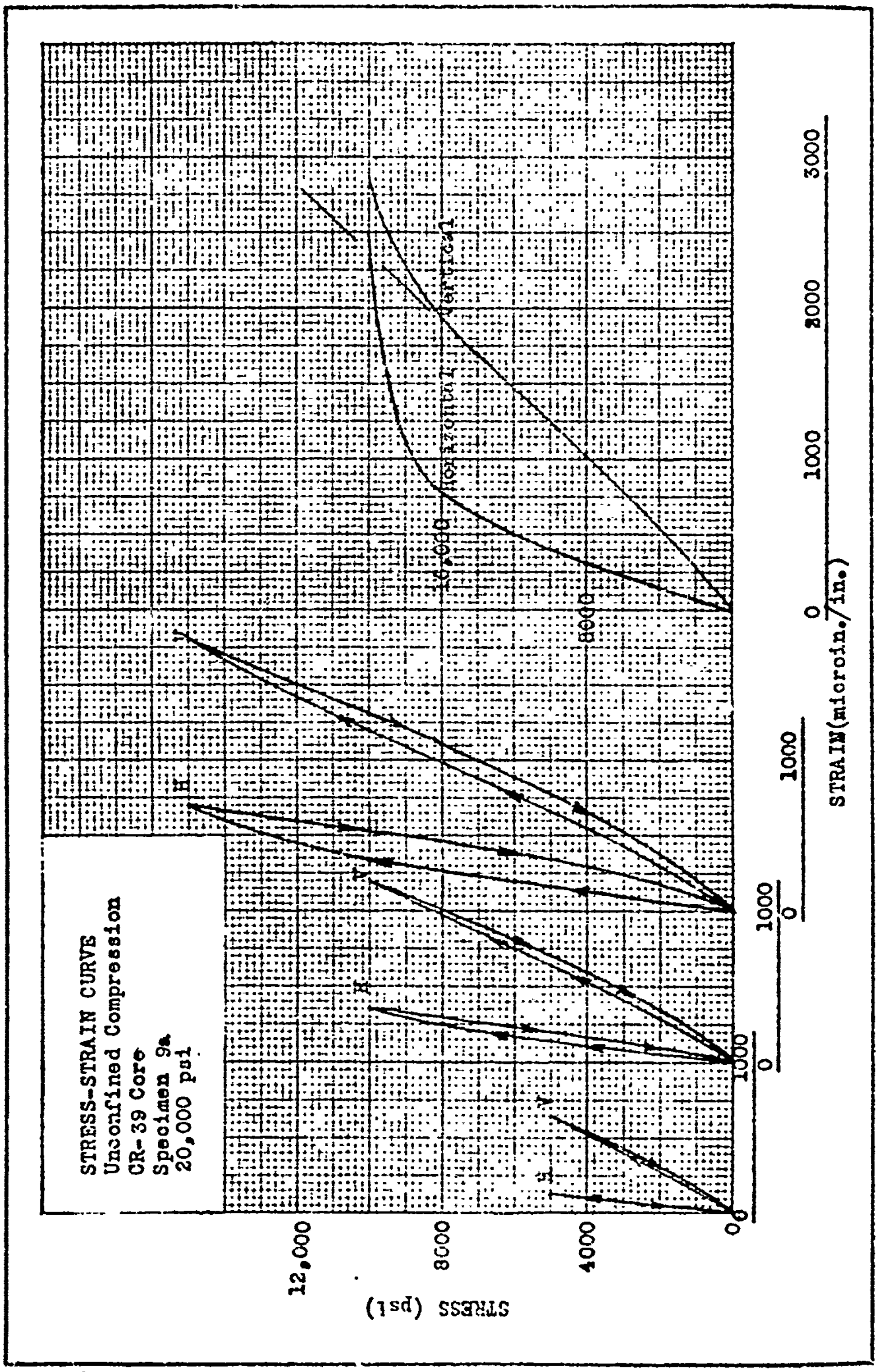
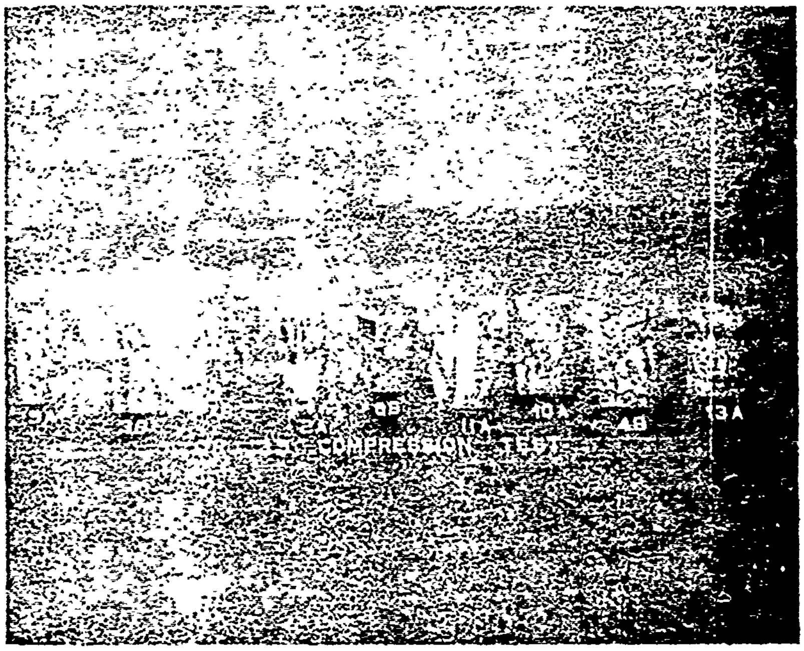

STRESS-STRAIN CURVE
Unconfined Compression
CR-39 Core
Specimen 9a
20,000 psi
STRESS (psi)
STRAIN(microin./in.)
12,000
8000
4000
0
1000
2000
3000
H
V
16,000
8000
Horizontal
Vertical

PLATE 4



Posttest Photograph

APPENDIX H

DATA REPORT - HOLE CR-42 CORES

27 SEPTEMBER 1968

WARREN SITING AREA

Core No. 2 (Hole CR-42)

1. Twenty pieces of core were received from the Warren area, designated CR-42 core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	38
A	2	38
A	3	39
A	4	40
A	5	41
A	6	41
A	7	42
B	8	84
B	9	85
B	10	86
B	11	87
B	[illegible]	88
B	13	89
B	14	90
B	15	90
B	16	91
C	17	185
C	18	186
C	19	186
C	20	187

2. The hole from which the core was taken was located in Albany County, Wyoming, township 13N, range 72W, section 9. All core was drilled vertically. Specimens were cut as required for the various tests; each segment of the specimen was given a letter designation signifying the section cut; for example, specimen 17a was the first test piece cut from specimen 17.

Warren Siting Area: Core No. 2 (CR-42); Series I Tests

Results

Petrographic examination

1. About 15 ft of NX rock core from three depths in core hole CR-42 in Albany County, Wyoming, was received in September 1968 for testing. The three pieces of the core that were used for petrographic examination are identified below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-2(A)	1	37.9	About 1/2
SAMSO-2 DC-2(M)	13	89.5	About 1/3
SAMSO-2 DC-2(T)	20	188.0	About 1/2

2. Piece 1 appeared to be the most weathered or altered; piece 13 the least affected, and piece 20 was more like piece 1. Aside from this variation in physical condition, all the core was similar in appearance.

3. Representative portions of piece 1 and of piece 13 were ground to pass a No. 325 sieve (44µ) and examined by X-ray diffractometry using nickel-filtered copper radiation.

4. Two thin sections were made from piece 13 and examined with a polarizing microscope.

5. Piece 20 was sawed axially, and this surface was photographed.

6. All of the rock was logged in the field as red granite with limonite staining numerous fractures. Additional examination in the laboratory indicates that granite is a suitable name for this rock.

7. There were numerous near vertical iron-stained open joints and many horizontal fractures in the core that was tested in this laboratory. Most of the horizontal breaks were fresh and appeared to be due to the drilling. The iron staining on joint surfaces indicated that these were old breaks. Most of the iron staining was due to limonite (tan) but that on piece 13 was due to hematite (red). This difference in color indicates less weathering in piece 13.

8. The rock is composed of montmorillonitic clay, quartz, potash feldspar (microcline), plagioclase feldspar, hornblende, and small amounts of mica and an opaque mineral. Some of the feldspars, mostly the plagioclase, show some alteration to a clay mineral.

9. The presence of more montmorillonitic clay in piece 1 than in piece 13 confirms the visual impression that piece 13 is fresher rock.

10. The rock is coarse-grained with the maximum grain dimension ranging up to about half an inch (photograph 1).

11. An estimated composition for this rock is shown below:

	%
Quartz	20
Microcline	30
Plagioclase	40 - 45
Hornblende	5
Clay	up to 5 - 10

These numbers were obtained by comparison with an X-ray pattern of U. S. Geological Survey standard granite G-2 and by consideration of its composition.*

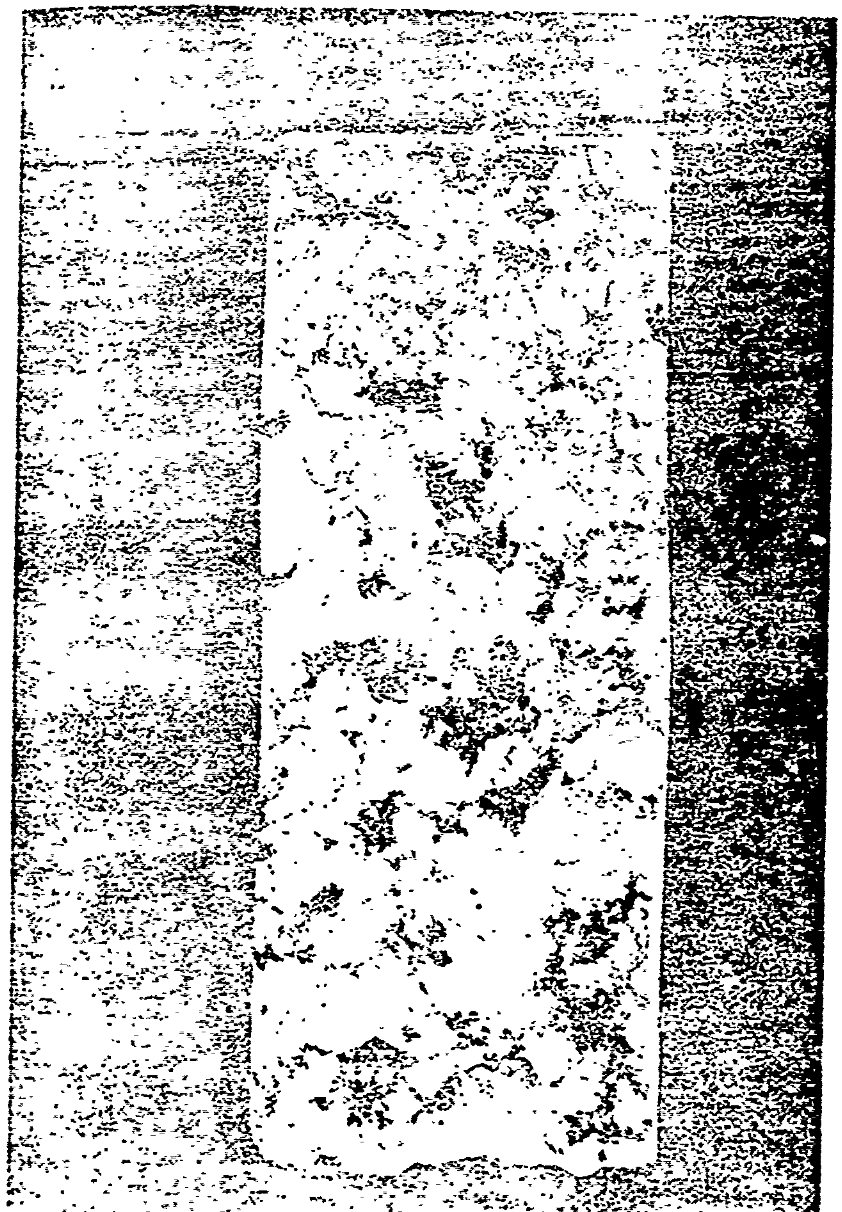
Schmidt number, specific gravity, porosity, and tensile strength

12. Three specimens from each depth interval were selected for the basic tests. Results are given below:

	Schmidt				Tensile
Core	Rebound Number	Standard Deviation	Specific Gravity	% Porosity	Strength, psi
	Sample A - 40-ft Depth				
26	46.9	6.79	2.664	0.7	600
36	48.3	4.25	2.664	0.5	720
76	52.6	6.07	2.674	0.0	820
Avg	49.3	5.70	2.667	0.4	710
	Sample B - 90-ft Depth				
9a	49.8	4.65	2.674	0.4	820
12c	51.9	3.37	2.668	0.4	850
15b	51.2	4.77	2.669	0.5	950
Avg	51.0	4.25	2.671	0.4	890

(Continued)

* Chayes, F., "Modal composition of U.S.G.S. reference sample G-2." *Geochimica et Cosmochimica Acta*, vol 31, No. 3, pp 463-64 (1967).



Photograph 1. Sawed surface of piece 20, depth 188 ft, magnification, X1.

Warren Siting Area: Core No. 2 (CR-42); Series I Tests

(Continued)

Core	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
	Sample C-185-ft Depth				
17b	47.5	3.87	2.660	0.5	680
18a	48.7	4.83	2.669	0.0	700
20a	52.8	3.44	2.660	1.0	890
Avg	49.7	4.05	2.663	0.5	760

13. The results indicate that the CR-42 core is less dense and more porous than the Laramie core; however, it may be considered a hard, dense rock. Difference in the core with depth is not pronounced in the data from the basic tests. The variation, as indicated by the standard deviation of the rebound number, is greater than the Laramie core, due possibly to the numerous small fractures and/or constituents of the rock. The tensile strength is very much lower than the Laramie core (780 versus 1400 psi), possibly due also to the numerous small fractures. Posttest photographs of the test specimens are given in plate 1.

Shear tests

14. Direct, single plane shear tests were conducted on three samples from the 90-ft depth interval. Due to the larger diameter of the CR-42 core, the 2.38-in.-diameter shear blocks were used. Shear strengths of 2160, 1700, and 1870 psi were obtained on samples 8, 9b, and 9c, respectively. Again, the average strength, 1910 psi, was somewhat lower than the Laramie core (2420 psi).

Unconfined compressive tests

15. Conventional unconfined compressive tests were conducted on specimens from the upper and lower depth intervals and cyclic compressive tests on specimens from the middle depth interval. Results are given below:

Core No.	Depth, ft	Unconfined Compressive Strength, psi
2a	38	13,200
3a	39	13,300
7a	42	16,300
Avg	40	14,270

(Continued)

(Continued)

Core No.	Depth, ft	Unconfined Compressive Strength, psi
12a	88	23,000
13a	89	20,200
15a	90	22,300
Avg	89	21,830
17a	185	17,100
18a	186	19,900
19a	185	17,200
Avg	185	18,070

..e compressive strength results tend to substantiate the observations ..the petrographer--the core from the 90-ft depth is somewhat better ..n the upper or lower areas sampled.

16. All specimens had two vertical and two horizontal electrical ..sistance strain gages affixed in order to measure strain during ..ting. The cycled specimens were unloaded at 5000-psi intervals. ..ess-strain curves are given in plates 2-10. Most of the specimens ..ibited a stress-strain relationship of the plastic-elastic type, i.e., ..tial "plastic" crack closing, followed by a definite steeper linear ..tion. The hysteresis loops were essentially closed; little residual ..rain was evident. To compute the deformation moduli, a tangent at ..percent of the ultimate strength was constructed as a dashed line .. the stress-strain curves. A posttest photograph of the test speci-.., plate 11, shows the nature of failure, steep sided coning, ..valent in compressive tests of brittle rock.

..li of deformation

17. Young's modulus, shear modulus, bulk modulus, and Poisson's ..io were computed on three samples by the dynamic (fundamental ..quency) method and on the unconfined compressive strength specimens ..atically at approximately 50 percent of the ultimate strength. Results ..e given below:

..	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
.	8.19	3.40	4.55	0.20
.	7.82	3.53	3.34	0.11
	5.32	2.37	2.27	0.11

(Continued)

Warren Siting Area: Core No. 2 (CR-42); Series I Tests

(Continued)

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Statically		
2a	10.21	4.16	6.18	0.22
3a	8.48	3.73	3.92*	0.14*
7a	10.62	4.11	8.39	0.29
12a	9.75	4.06	5.42	0.20
13a	9.88	3.77	8.68	0.31
15a	10.25	4.19	6.18	0.22
17a	9.21	4.05	4.22*	0.14*
18a	9.80	3.74	8.61	0.31
19a	11.77	4.72	7.87	0.25
Avg Static	10.00	4.06	7.33	0.27

* Deleted from average.

18. The moduli are comparable to those obtained on the Laramie core. Computation of static results at 50 percent of the ultimate strength results in higher moduli compared to the dynamic results due to the higher stress levels involved. Low bulk moduli on specimens 3a and 17a are the result of low Poisson's ratio obtained on these two specimens.

Velocity measurements

19. The compressional velocity was determined directly as the sonic propagation velocity, and the shear wave velocity was determined from the torsional frequency obtained in the moduli determinations.

Core No.	Compressional Pulse Velocity, fps	Shear Velocity, fps
4	16,780	9560
12	15,610	9680
17	13,615	7980
Avg	15,340	9070

The shear velocity is approximately 59 percent of the compressional velocity.

Warren Siting Area: Core No. 2 (CR-42); Series I Tests

Conclusions

20. The CR-42 core is identified as a granite with limonite ...aining numerous fractures. The rock was not as homogeneous with ...th nor as competent as was the Laramie core. Consensus results ... some physical properties for the core tested compared to the ...amie core are:

Property	Laramie Core	CR-42 Core
...ecific gravity	2.72	2.57
...rcent porosity	0.0	0.5
...mpressive strength, psi	21,600	18,000
...nsile strength, psi	1,400	780
...ung's modulus, psi x 10^6	11.8	10.0
...mpressional wave velocity, fps	19,800	15,300

Warren Siting Area: Core No. 2 (CR-42); Series II Tests

Results

Hydrostatic compression

21. Hydrostatic compressive tests were conducted on three specimens, one each to pressures of 9000, 18,000, and 36,000 psi. The specimens were prepared in a manner similar to the unconfined compressive tests except that the tests at 18,000 and 36,000 psi were conducted on 1.5-in.-diameter specimens recored from the NX size cores so as to have sufficient axial load capacity to fracture the specimens. Some difficulty was experienced with the gages on the CR-42 cores. The vertical gages on the specimen tested to 9000 psi (12b) and both vertical and horizontal gages on the specimen tested to 36,000 psi (4b) failed under the hydrostatic pressure. Stress-strain curves for the horizontal and vertical deformations for specimen 4a and the horizontal deformation for specimen 12b are given in plates 12, 13, and 14, respectively. Utilizing the results of loading cycles 3 and 4, the bulk modulus, K, was computed for specimen 4a from the relation:

$$K = \frac{\sigma}{\epsilon_1 + \epsilon_2 + \epsilon_3}$$

where:

σ = hydrostatic stress

ϵ_1 = vertical strain

$\epsilon_2 = \epsilon_3$ = horizontal strain

The bulk modulus was computed for specimen 12b by using the horizontal strain thrice.

Specimen No.	Maximum Stress, psi	Bulk Modulus, K, psi
12b	9,000	5.00
4a	18,000	6.67

The bulk moduli agree quite well with the dynamically determined moduli (paragraph 17). The almost equal strains obtained in the vertical and horizontal directions on specimen 4a indicate isotropy in this particular specimen.

Triaxial compression

22. Triaxial tests were conducted on the same specimens utilized for the hydrostatic tests at confining pressures equal to the hydrostatic pressures previously applied. Stress-strain curves are given in plates 15 and 16 for specimens 4a and 12b, respectively. Young's modulus, computed as the initial tangent, and Poisson's ratio for specimen 4a were 12.0 x 10^6 psi and 0.25, respectively.

23. The Mohr's circles for all tests are given in plate 17. The envelope was constructed utilizing the results of the unconfined, the 18,000, and the 36,000 psi triaxial tests of the weaker rock. An initial angle of shearing resistance of approximately 45 degrees and a slightly curving envelope are indicated for the less competent material. The unconfined strength (22,000 psi) and the one triaxial test at 9000 psi confining pressure on the better rock indicate a higher initial envelope angle, 52 degrees.

24. The compressional wave velocity was recorded during test to failure of two specimens, 4a and 4b. Equipment malfunction prevented measurements during test of specimen 12b. Results are given below:

Specimen 4a		Specimen 4b	
Axial Stress, psi	Wave Velocity, fps	Axial Stress, psi	Wave Velocity, fps
0	18,940	0	18,940
18,000 (hydrostatic)	20,830	36,000 (hydrostatic)	20,830
30,000	21,930	50,000	21,930
50,000	23,140	75,000	23,140
75,000	24,500	100,000	24,500
100,000	24,500	125,000	26,040
		150,000	26,040

Considerable difficulty was experienced in obtaining a valid wave picture. Also, the results should be considered only approximate due to the necessity of using the extremely small specimens (1.5 in. diameter, 3 in. long). However, indications are that the velocity does change somewhat under stress. A posttest photograph of the test specimen is given in plate 18.

Confined compression

25. Confined compression tests were conducted on two specimens prepared essentially as the triaxial test specimens. Confining pressure was applied to prevent lateral straining as axial load was applied by the

piston. Therefore, a pseudo one-dimensional state of stress was induced, from which can be computed a constrained modulus. The axial stress-strain curves are given in plates 19 and 20. The lateral stress required to maintain a condition of no lateral strain is given on the far left of the curves. The gages failed after 7500 psi lateral pressure had been applied to specimen 14a.

26. The constrained modulus, M_c, may be computed from theory of elasticity:

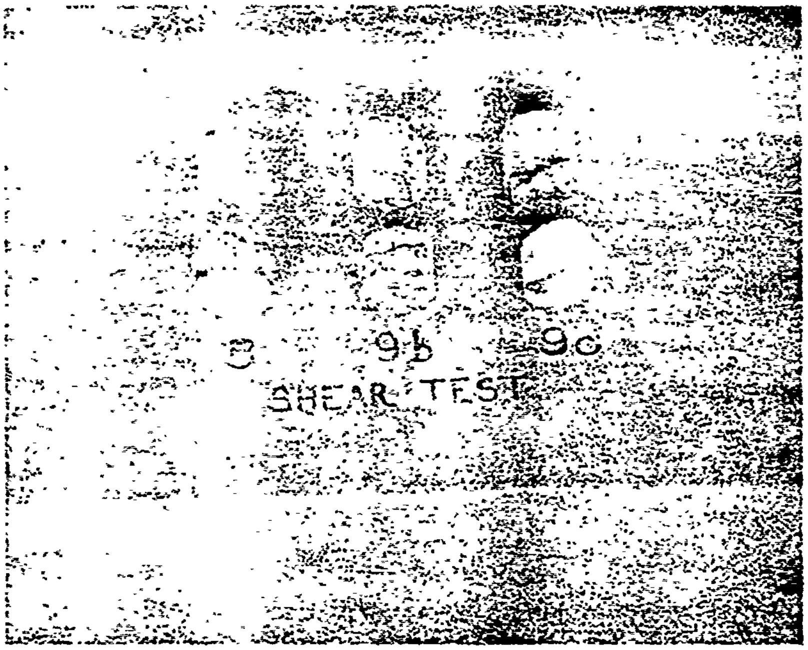
$$M_c = \frac{E\,(1-u)}{(1+u)(1-2u)}$$

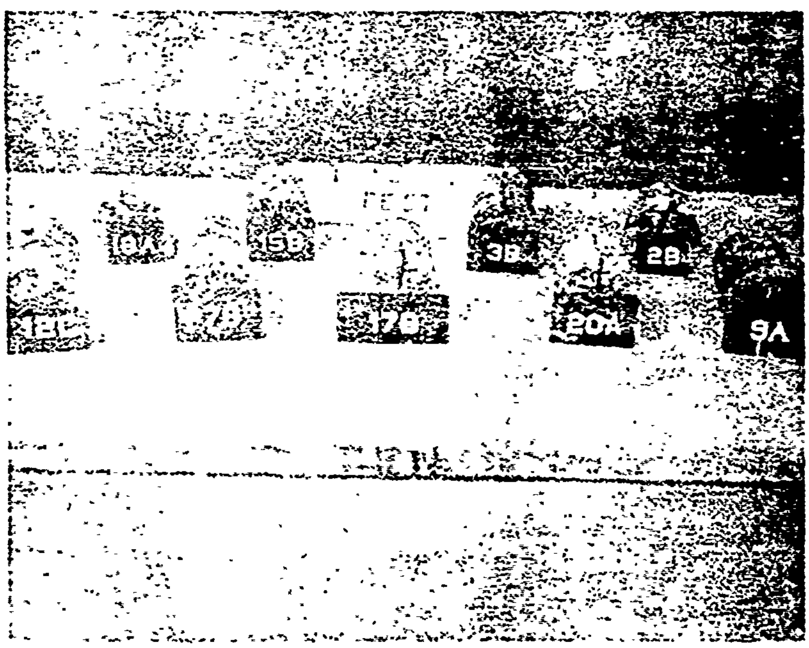
where:

E = Young's modulus

u = Poisson's ratio

Using the results from the triaxial test of the more competent material ($E = 12.0 \times 10^6$ psi; $u = 0.25$), the constrained modulus is computed to be 14.4×10^6 psi. The constrained modulus computed on the linear portion of the stress-strain curve for specimen 16a is approximately 15.0×10^6 psi. Good agreement is, therefore, indicated between the theoretical and experimental results.





Posttest Photographs

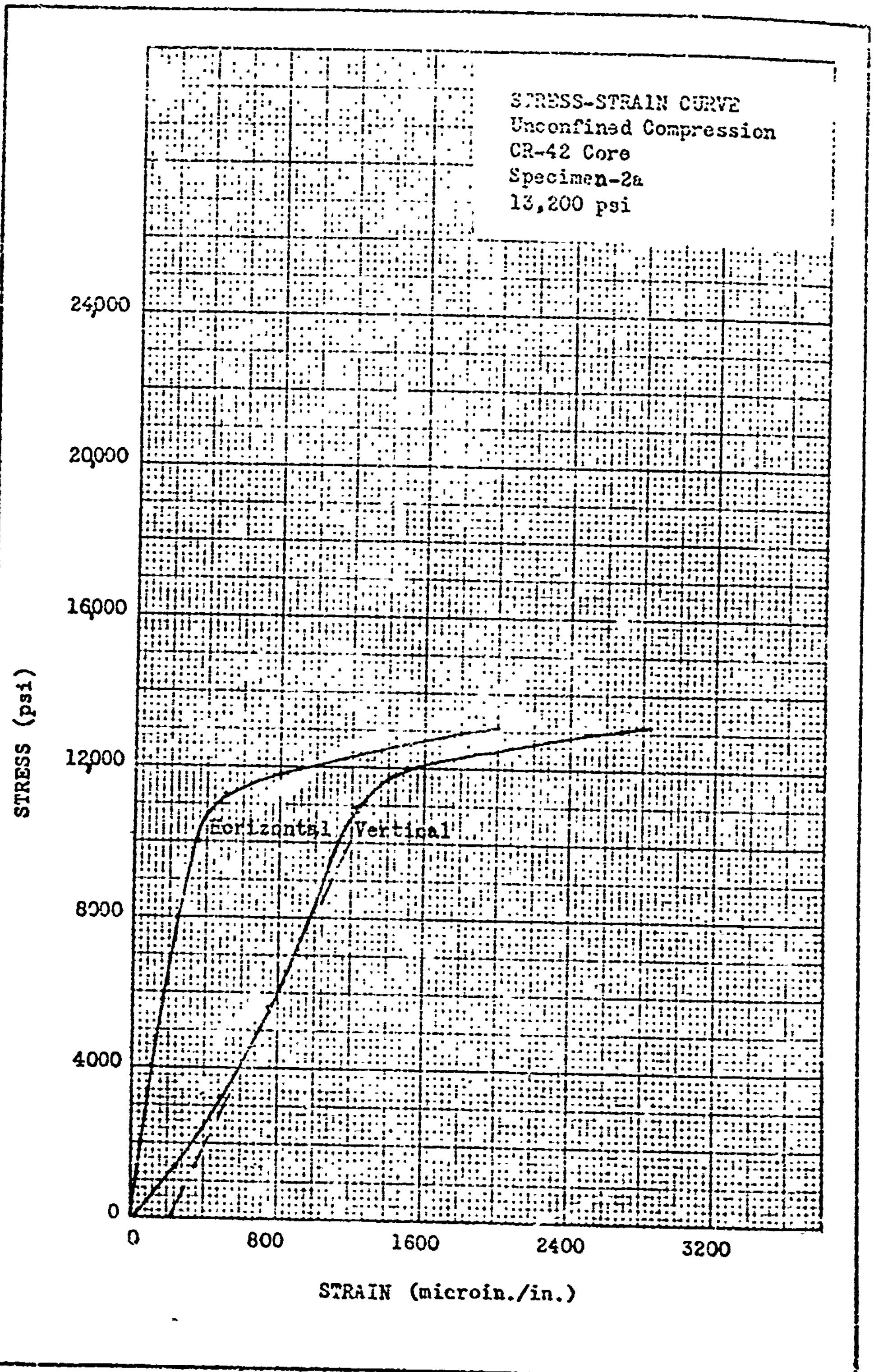

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen-2a
13,200 psi
STRESS (psi)
24000
20000
16000
12000
8000
4000
0
Horizontal
Vertical
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 2

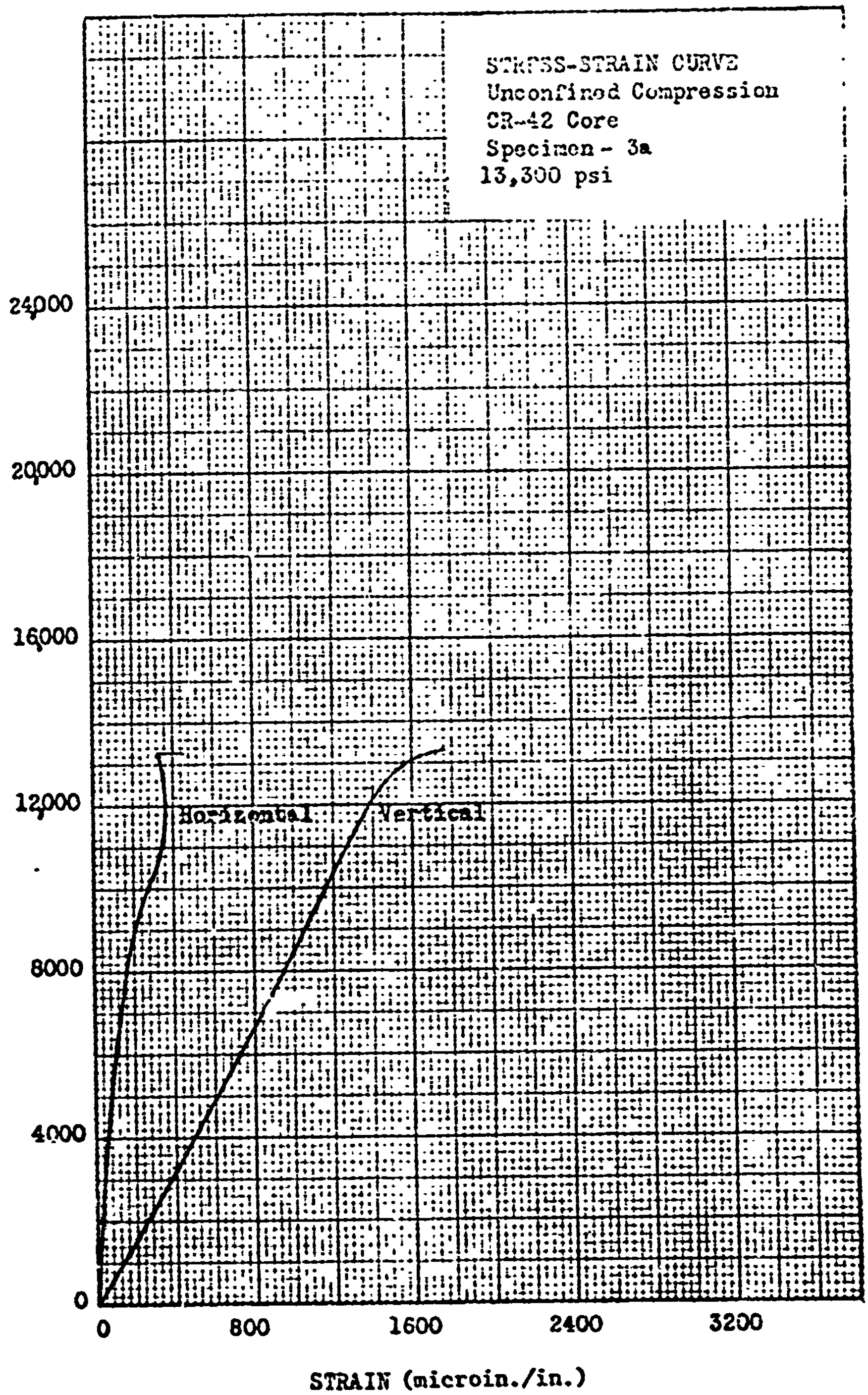

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen - 3a
13,300 psi
24000
20000
16000
12000
8000
4000
0
Horizontal
Vertical
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 3

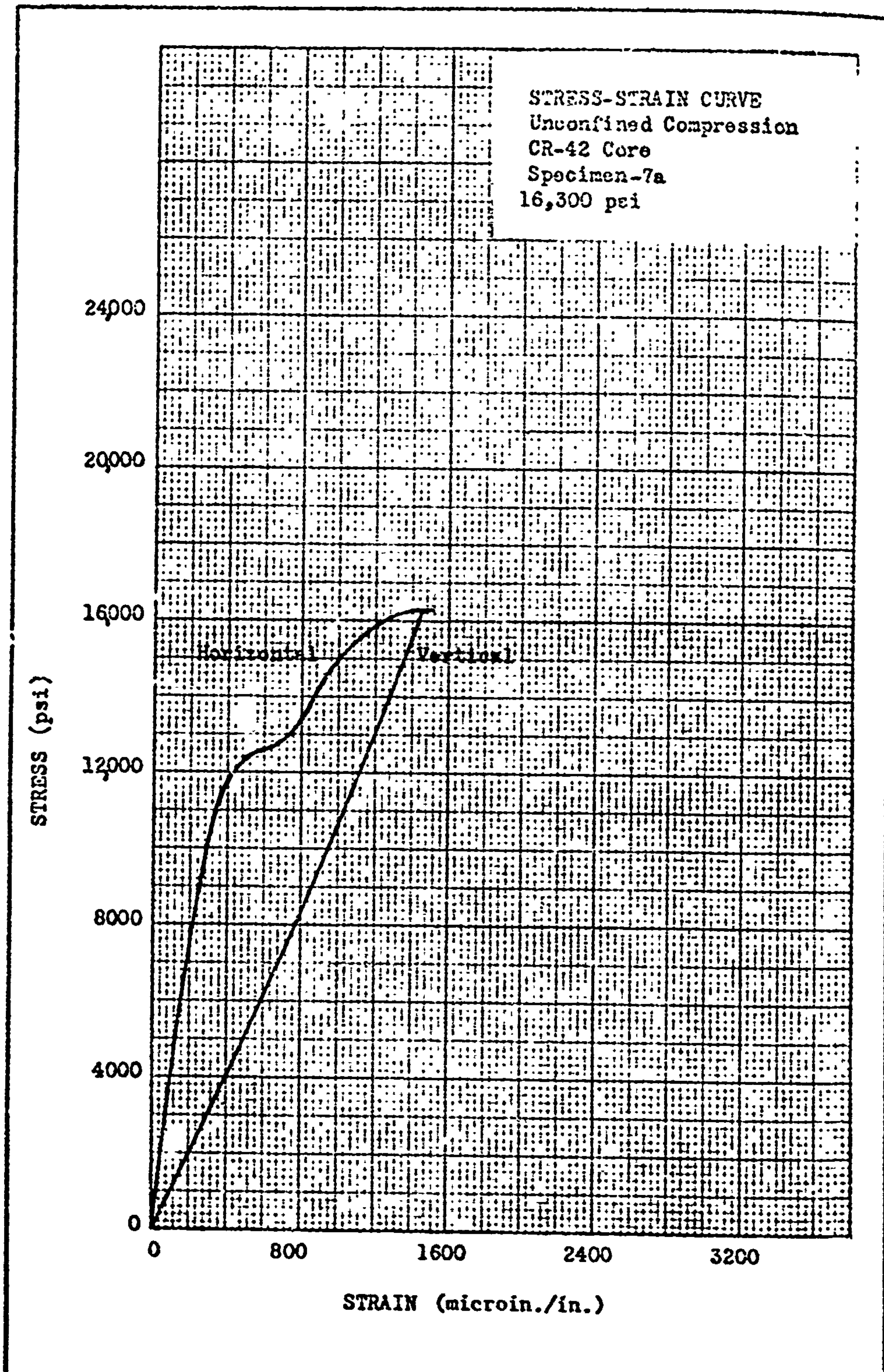

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen-7a
16,300 psi
24000
20000
16000
12000
8000
4000
0
Horizontal
Vertical
STRESS (psi)
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 4

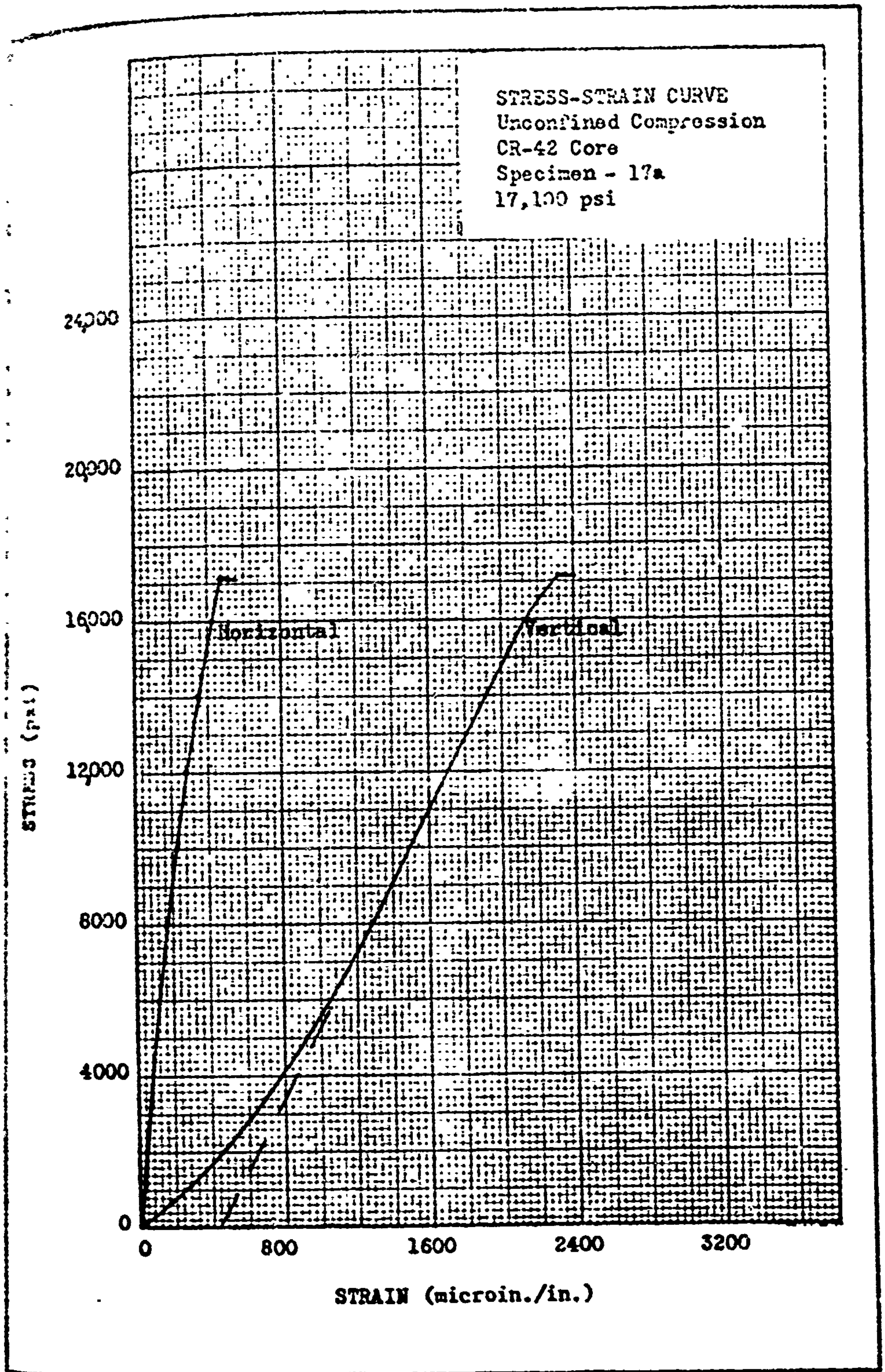

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen - 17a
17,100 psi
Horizontal
Vertical
STRESS (psi)
24000
20000
16000
12000
8000
4000
0
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 5

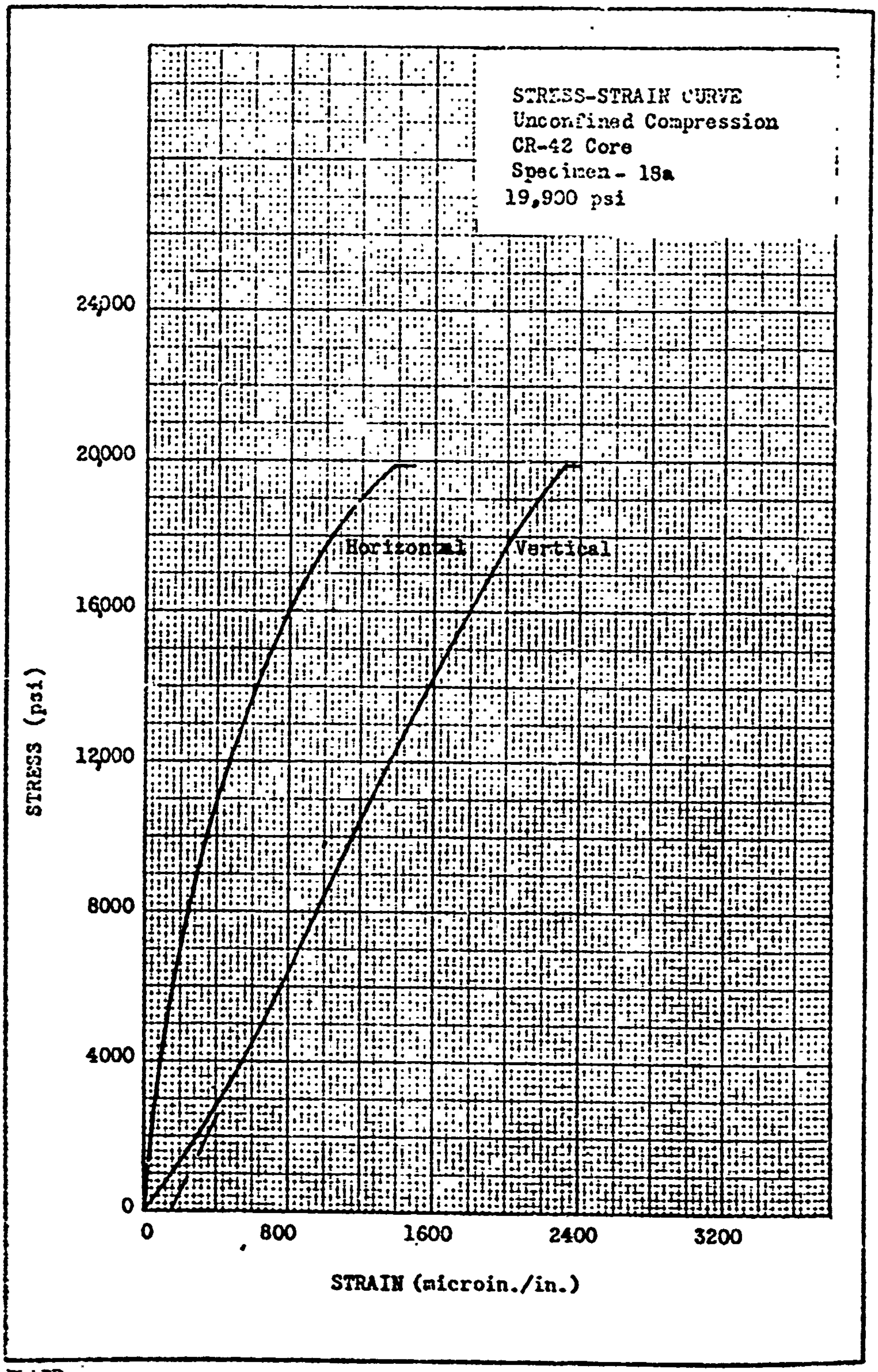

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen - 18a
19,900 psi
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
Horizontal
Vertical
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE c

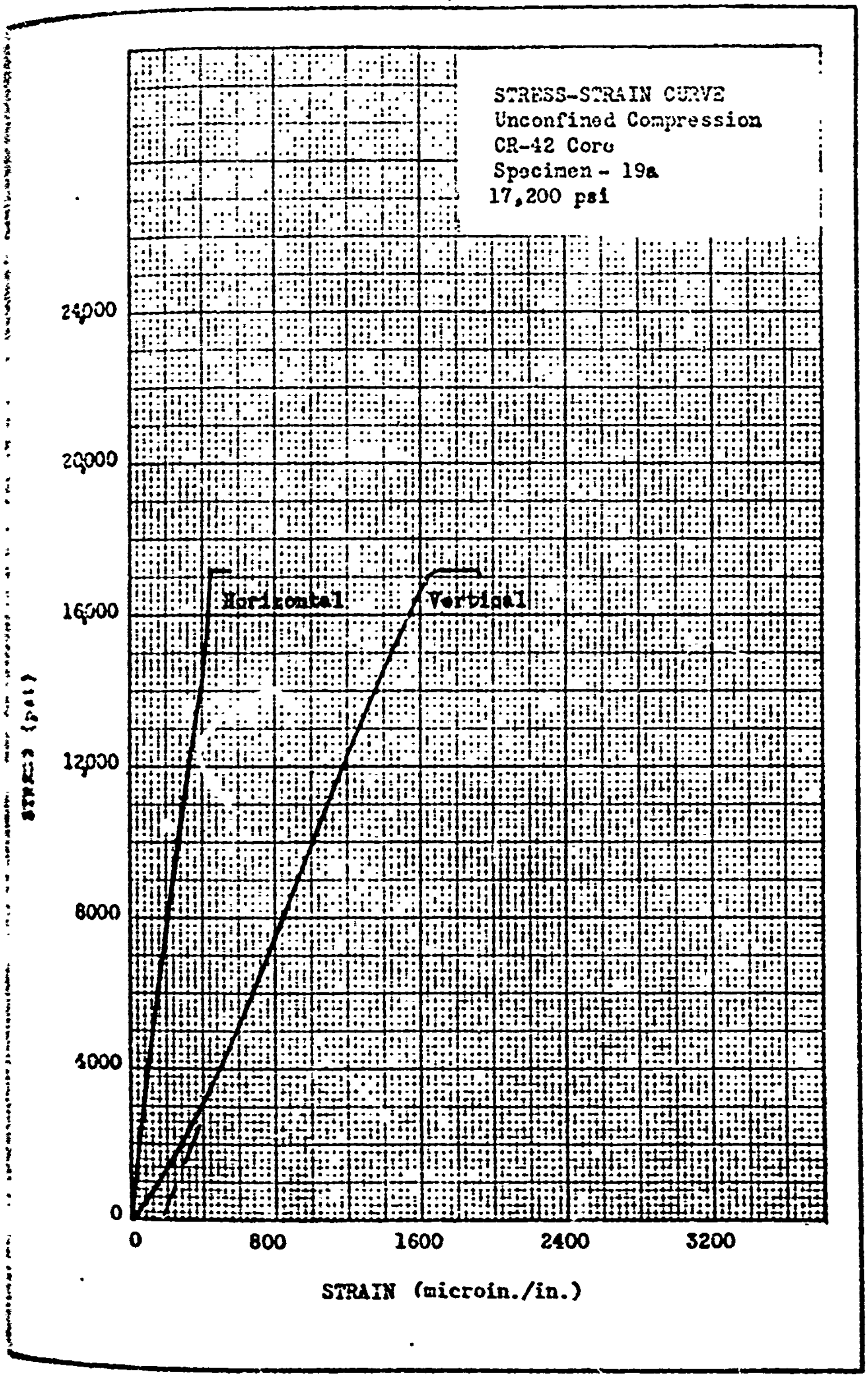

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen - 19a
17,200 psi
Horizontal
Vertical
24000
20000
16000
12000
8000
4000
0
STRESS (psi)
0
800
1600
2400
3200
STRAIN (microin./in.)

PLATE 7

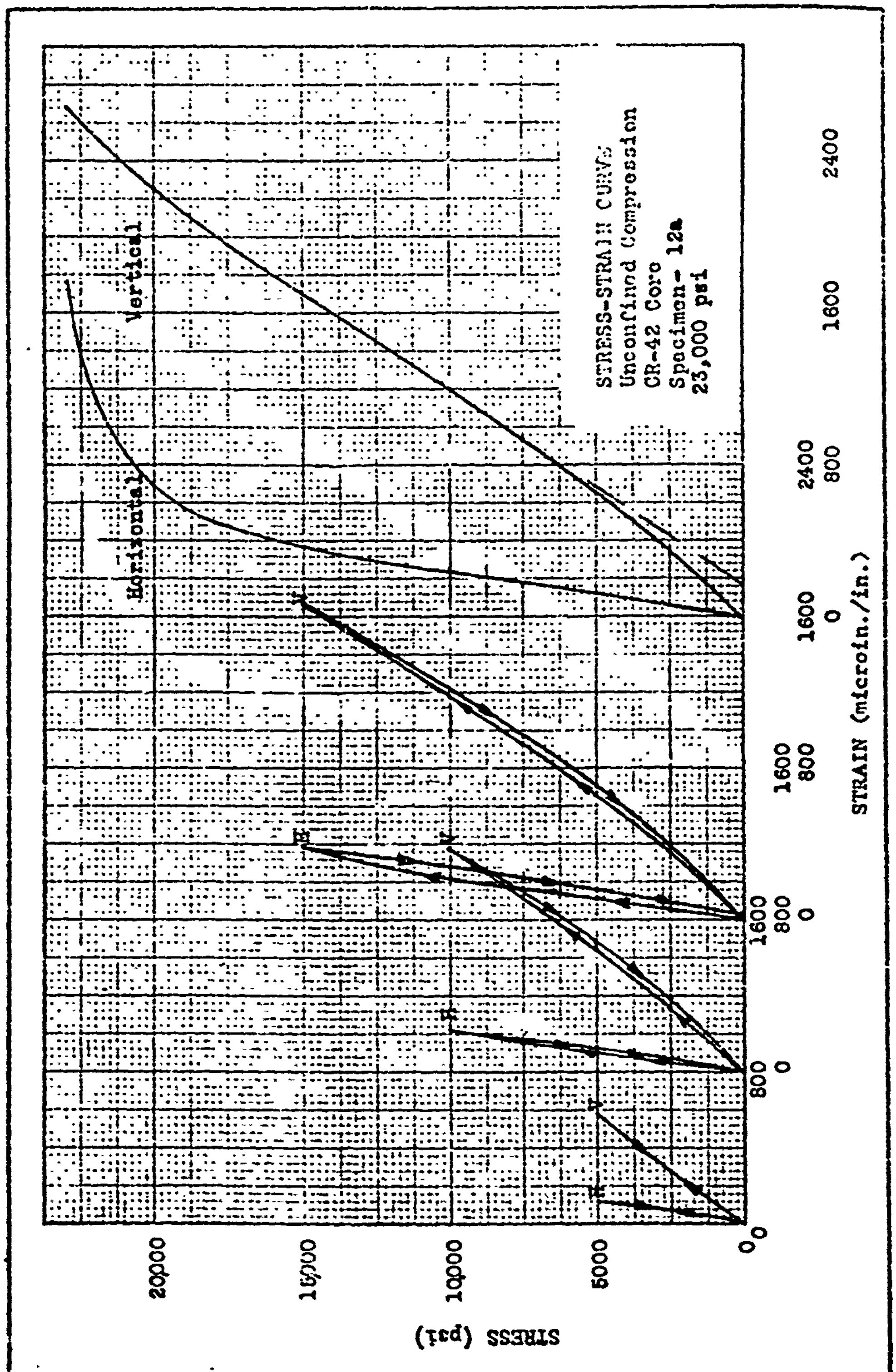

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen- 12a
23,000 psi
Vertical
Horizontal
H
V
STRESS (psi)
STRAIN (microin./in.)
0
5000
10000
15000
20000
0
800
1600
2400

PLATE 8

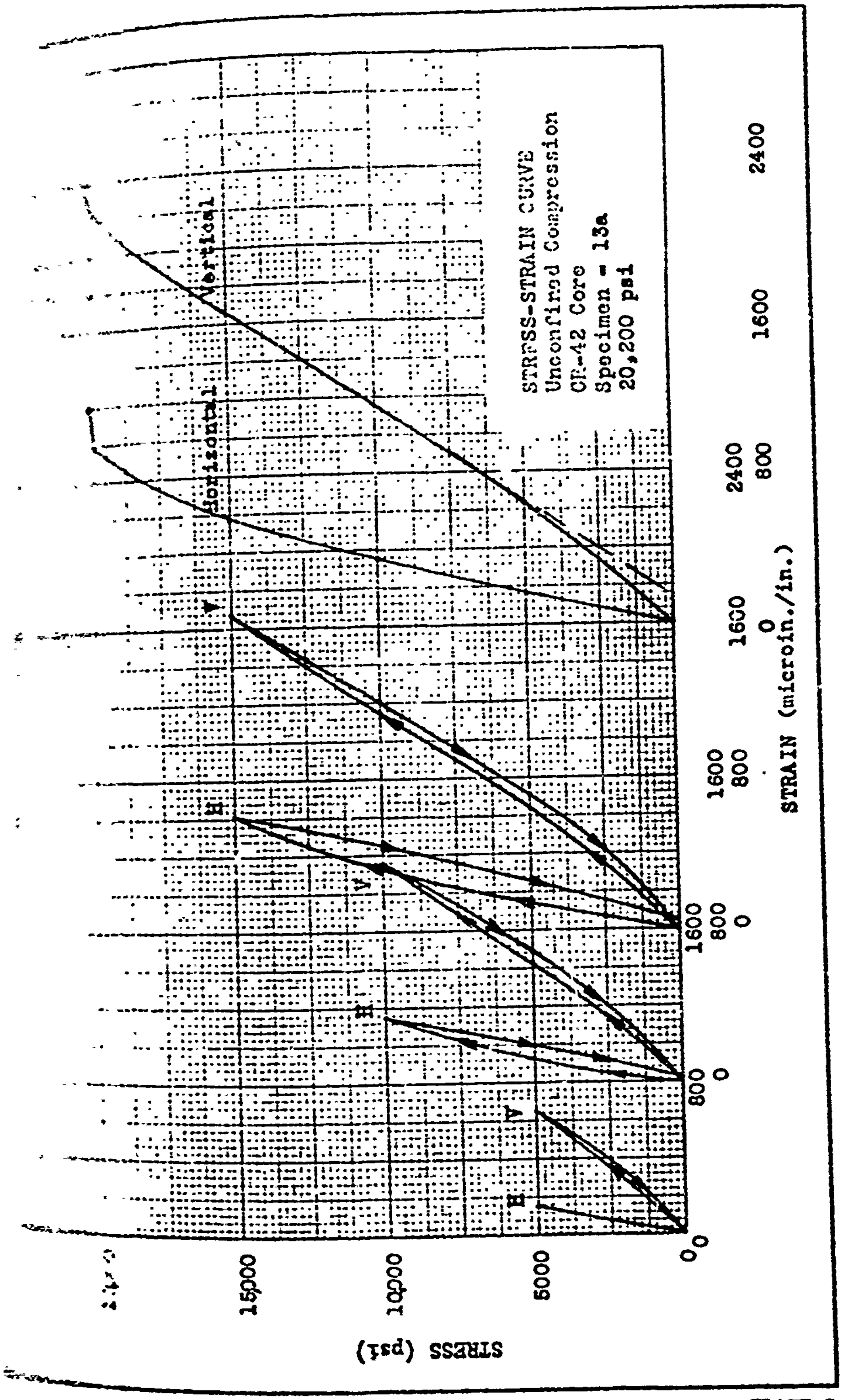

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen - 13a
20,200 psi
Vertical
Horizontal
STRAIN (microin./in.)
STRESS (psi)
15000
10000
5000
0
800
1600
2400
V
H

PLATE 9

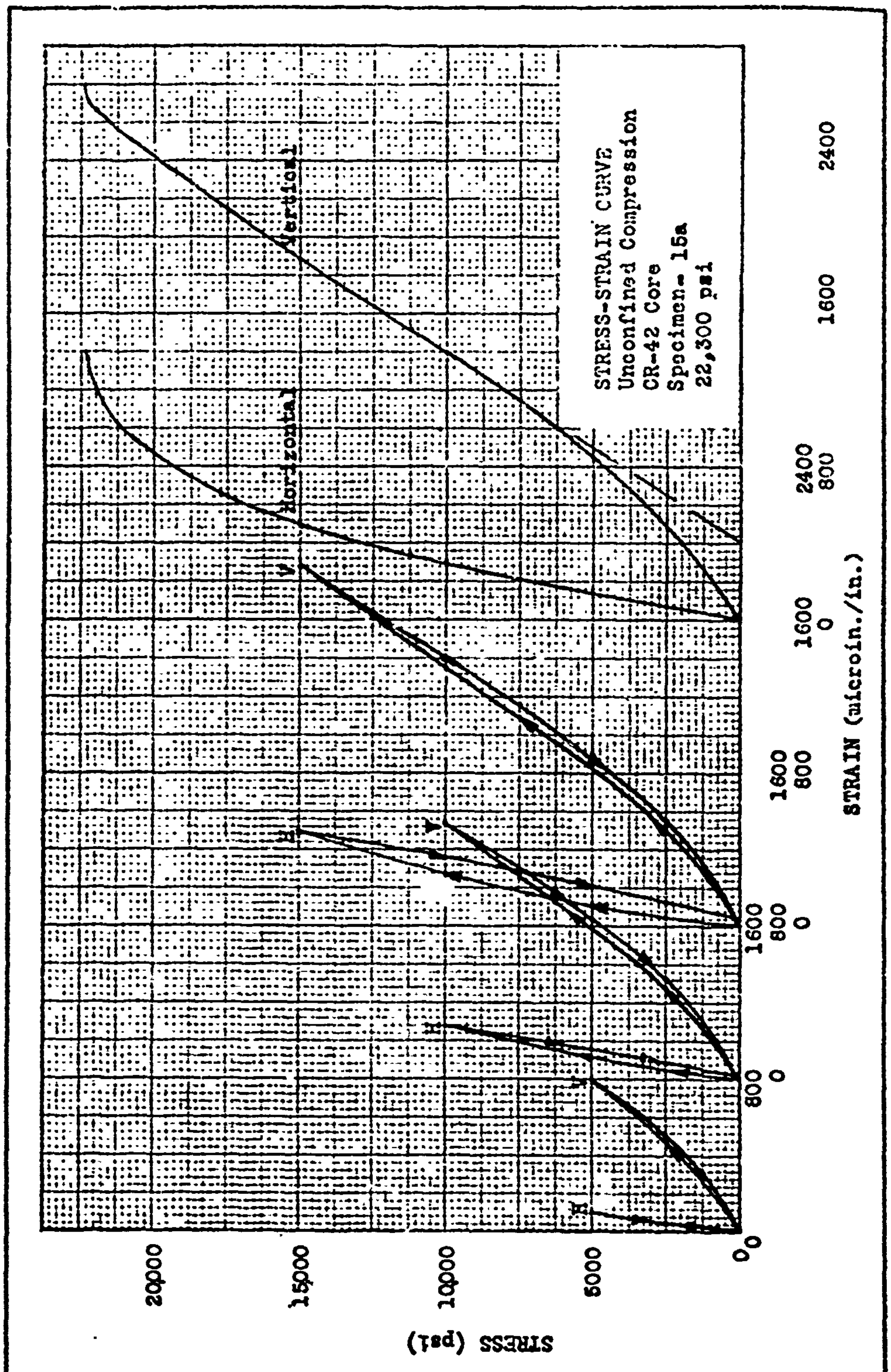
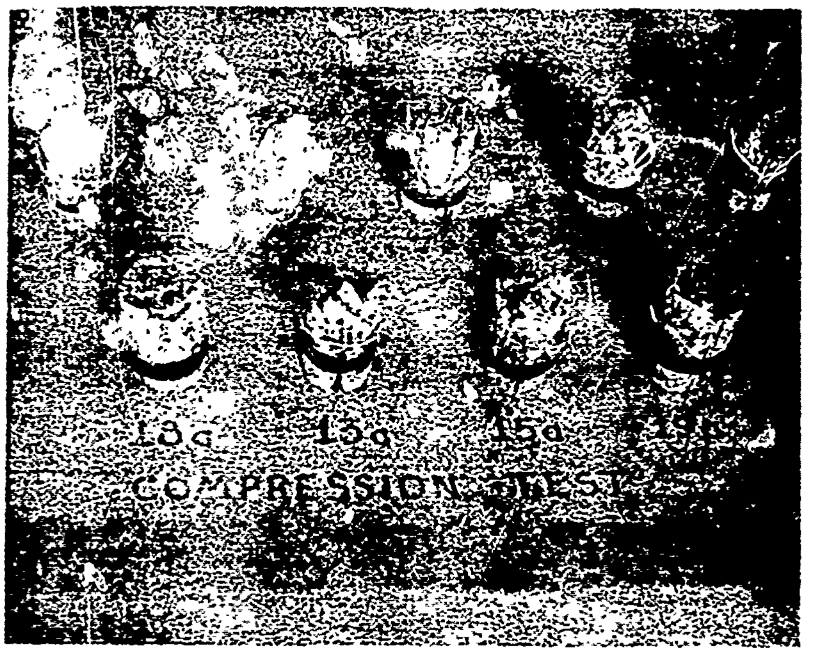

STRESS-STRAIN CURVE
Unconfined Compression
CR-42 Core
Specimen- 15a
22,300 psi
Vertical
Horizontal
STRESS (psi)
STRAIN (microin./in.)

PLATE 10



Posttest Photograph

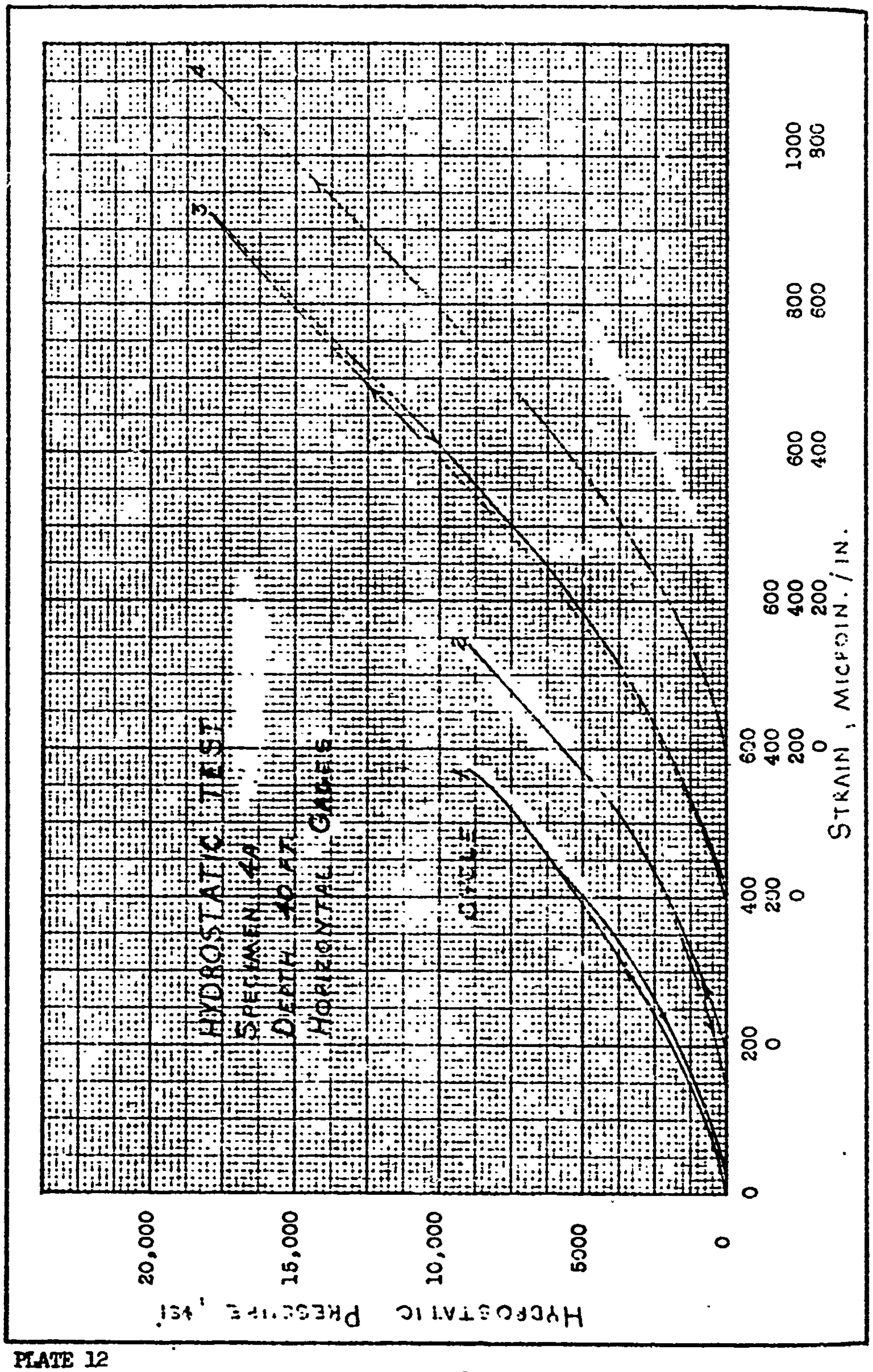

HYDROSTATIC TEST
SPECIMEN 4A
DEPTH 40 FT.
HORIZONTAL GAGES
CYCLE
1
2
3
4
HYDROSTATIC PRESSURE, PSI
20,000
15,000
10,000
5000
0
STRAIN, MICROIN./IN.
0
200
0
400
200
0
600
400
200
0
600
400
200
600
400
800
600
1000
800

PLATE 12

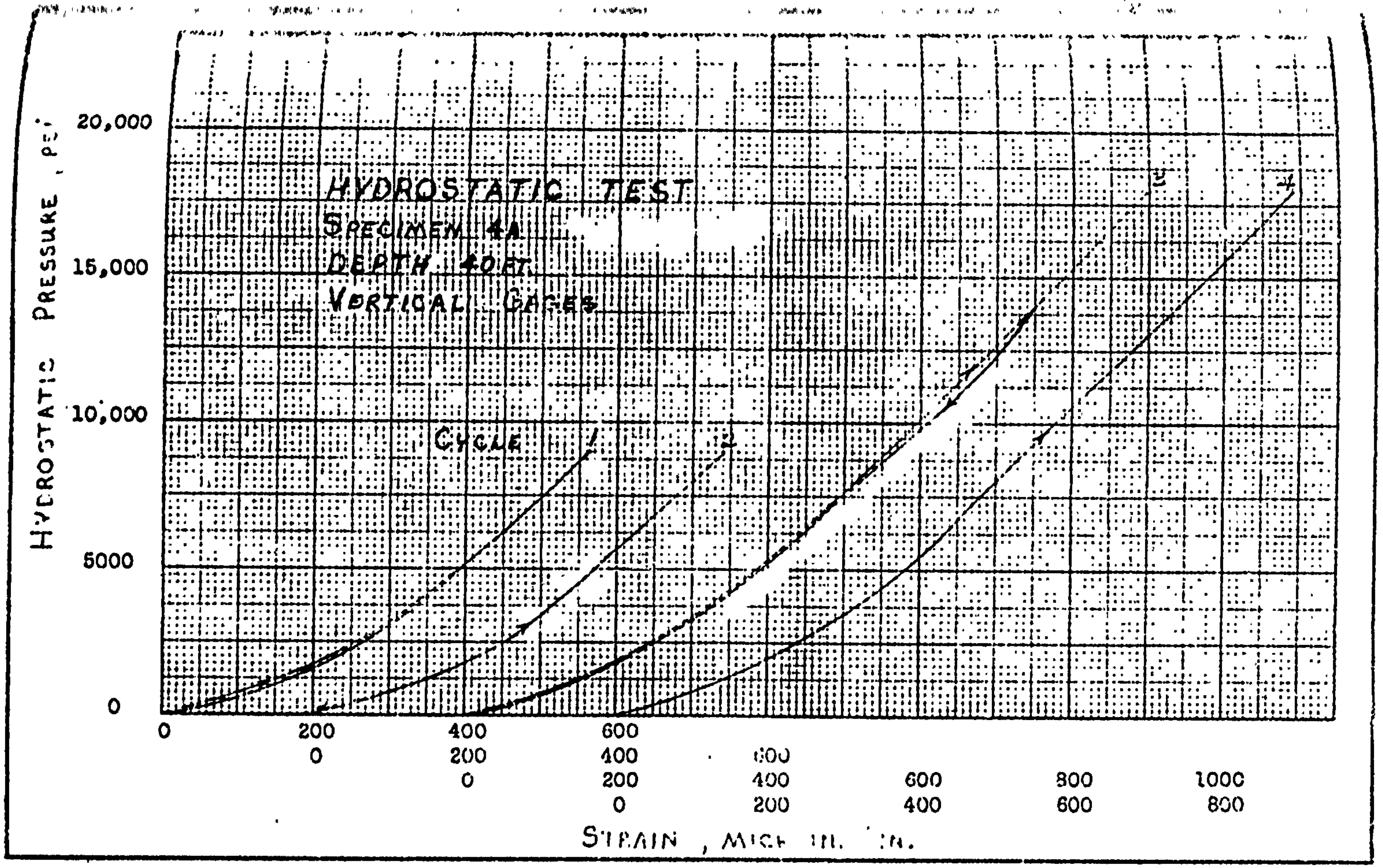

HYDROSTATIC TEST
SPECIMEN 4A
DEPTH 40 FT.
VERTICAL GAGES
CYCLE 1
2
3
4
HYDROSTATIC PRESSURE, PSI
20,000
15,000
10,000
5000
0
0
200
400
600
0
200
400
0
200
400
600
0
200
400
600
800
1000
800
600
400
STRAIN, MICRO IN./IN.

PLATE 13

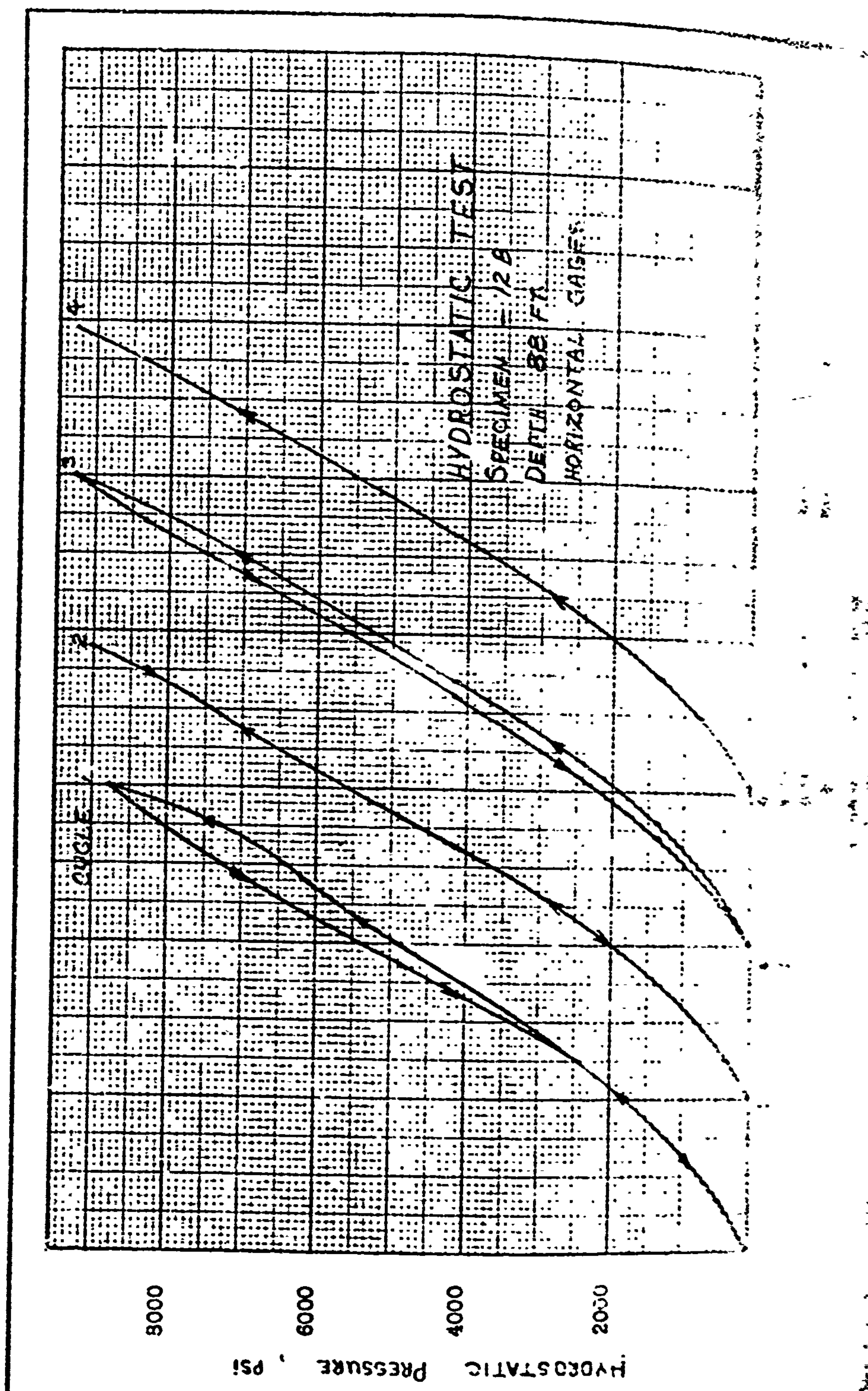
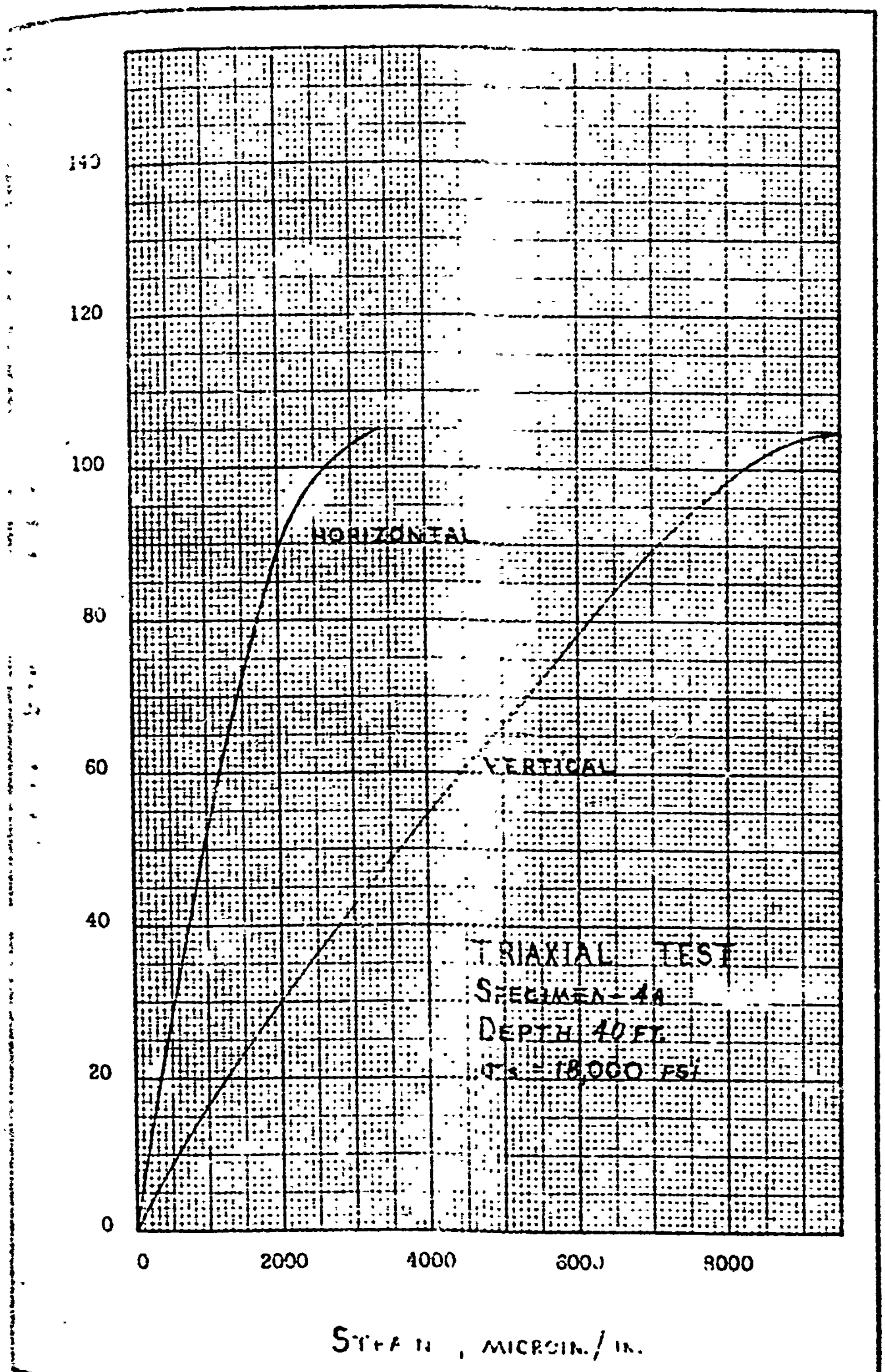

HYDROSTATIC TEST
SPECIMEN — 12 B
DEPTH 88 FT.
HORIZONTAL GAGES
CYCLE
1
2
3
4
8000
6000
4000
2000
HYDROSTATIC PRESSURE, PSI

PLATE 14



140
120
100
80
60
40
20
0
0
2000
4000
6000
8000
HORIZONTAL
VERTICAL
TRIAXIAL TEST
SPECIMEN-4A
DEPTH 40 FT.
STRAIN, MICROIN./IN.

PLATE 15

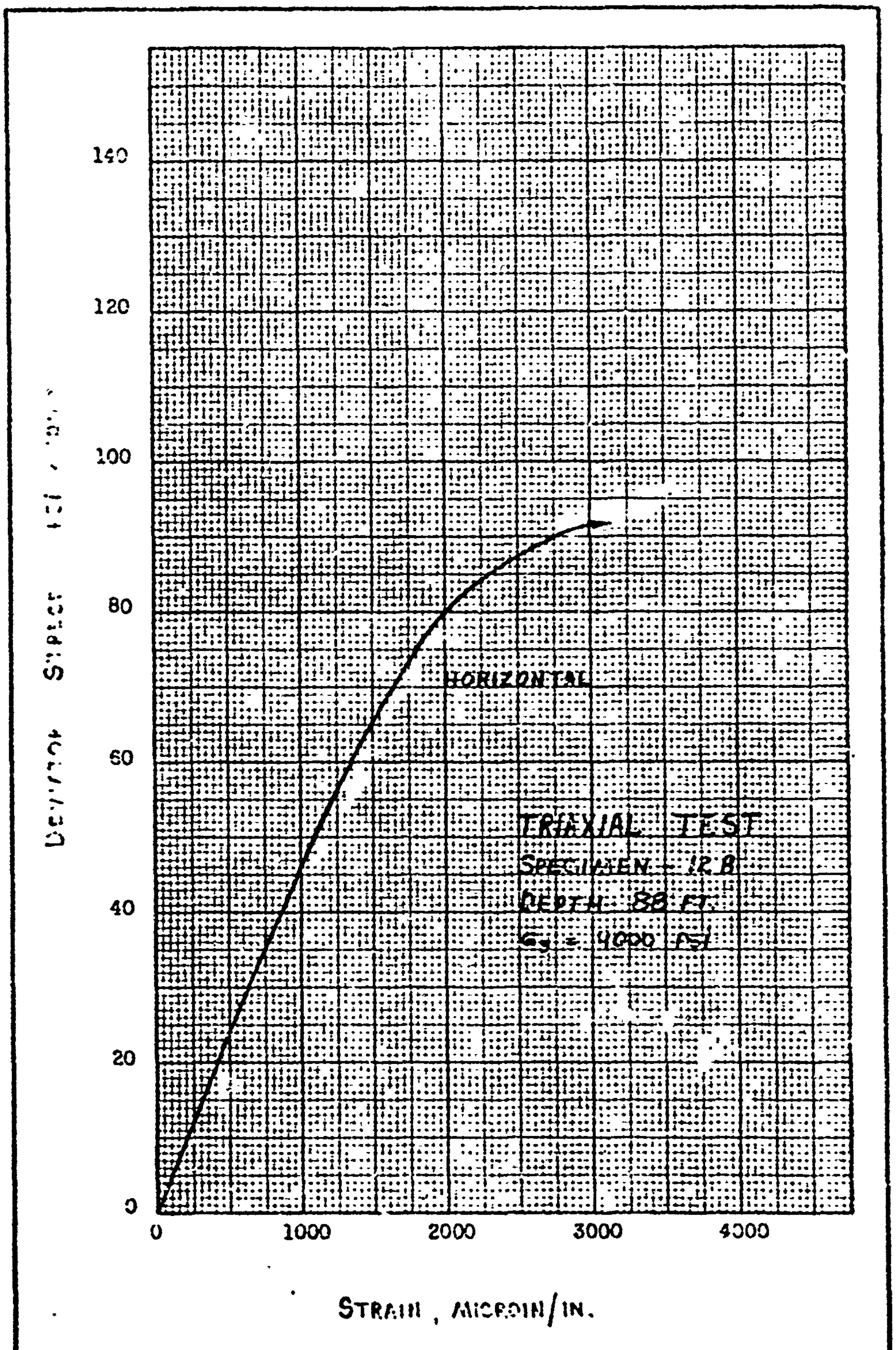
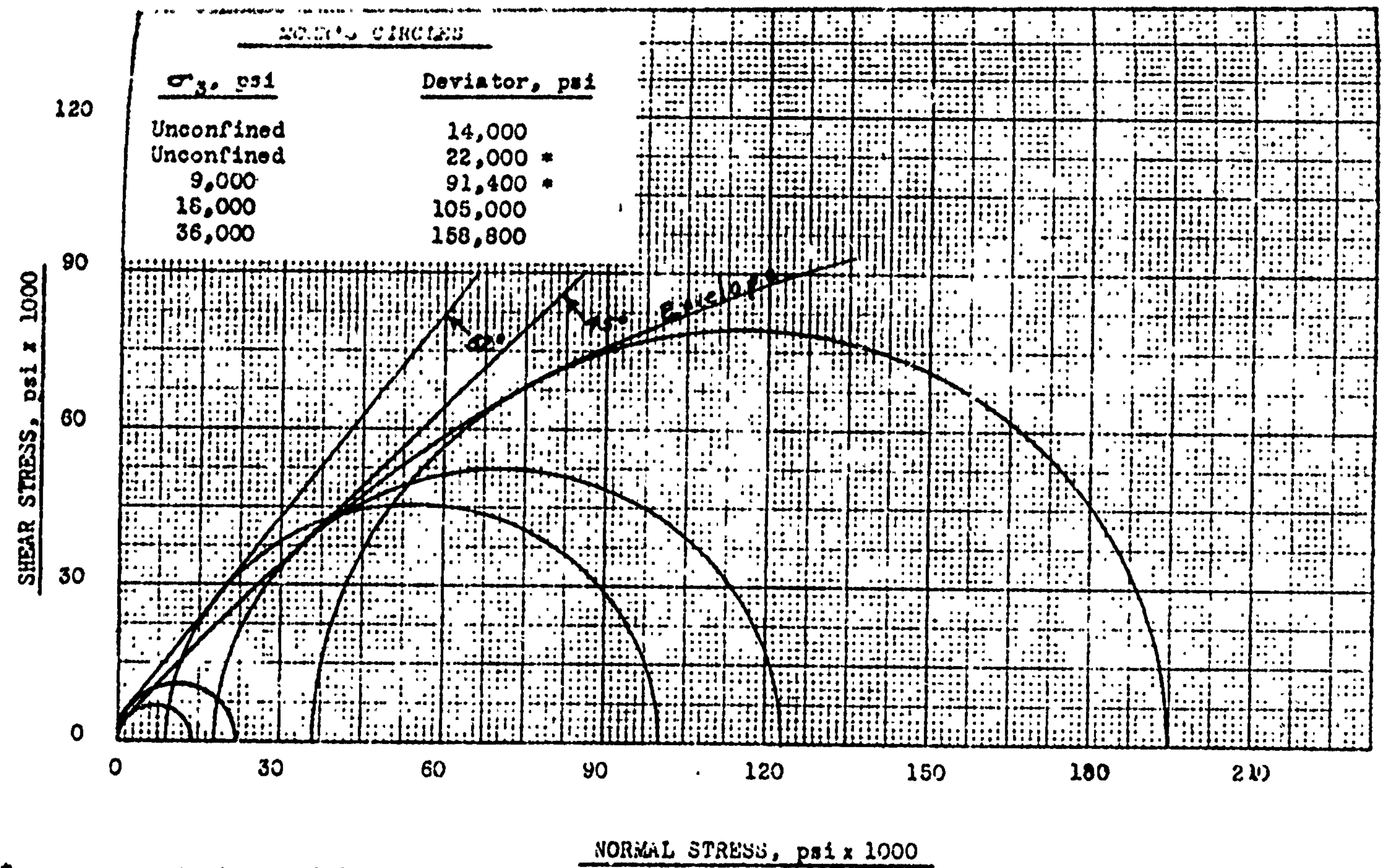
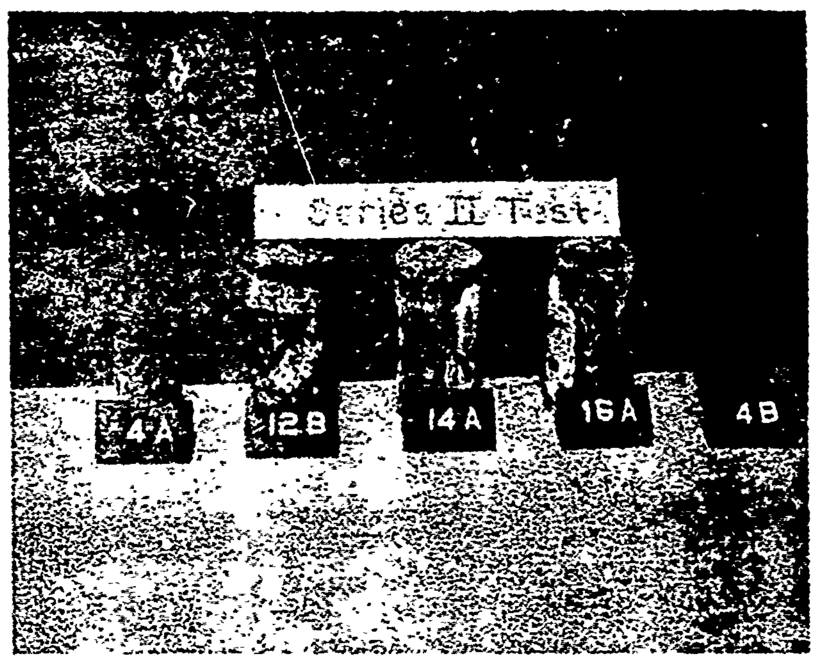

HORIZONTAL
TRIAXIAL TEST
SPECIMEN - 12 B
DEPTH 88 FT.
σ_3 = 4000 PSI
0
20
40
60
80
100
120
140
0
1000
2000
3000
4000
STRAIN, MICROIN/IN.

PLATE 16



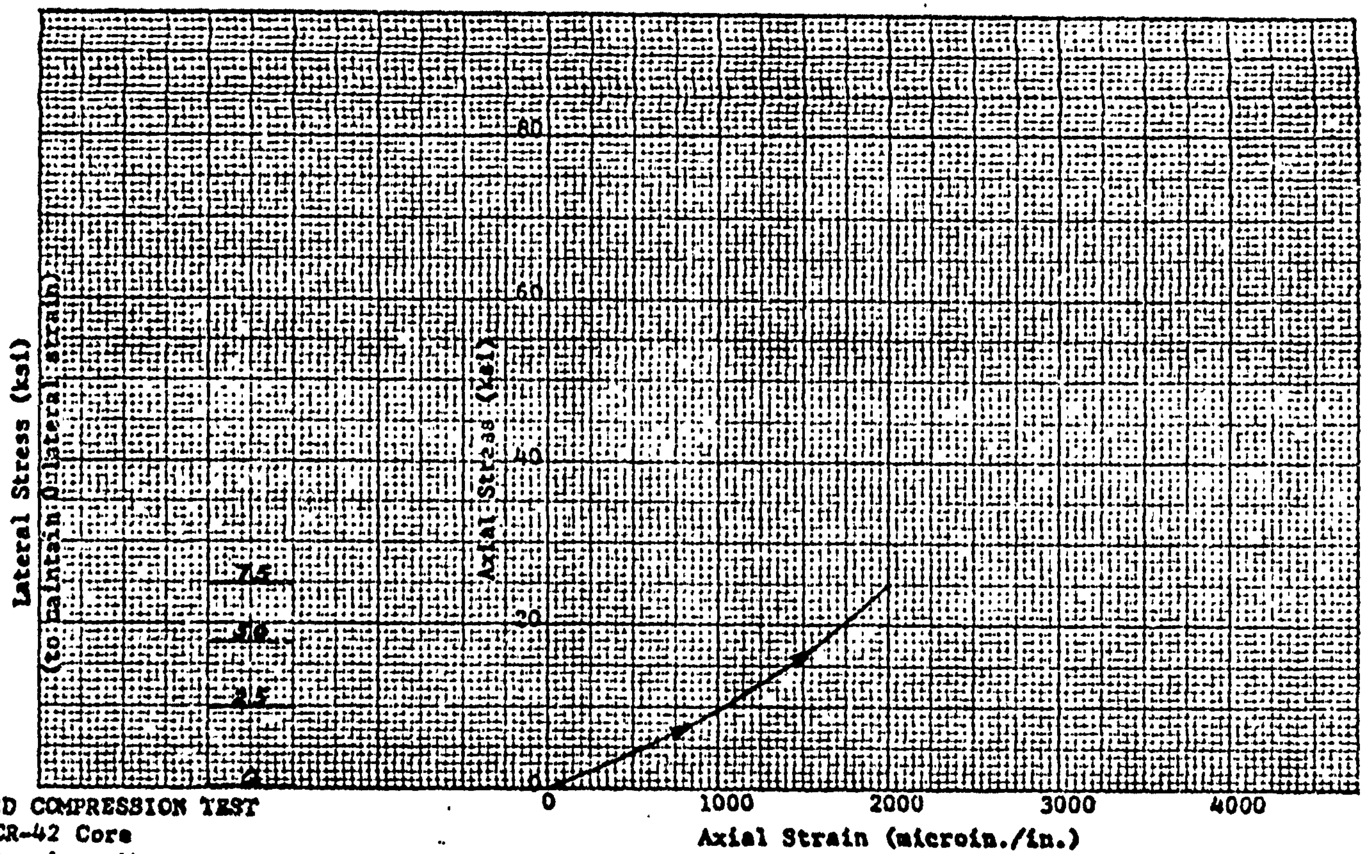
* more competent material

PLATE 17



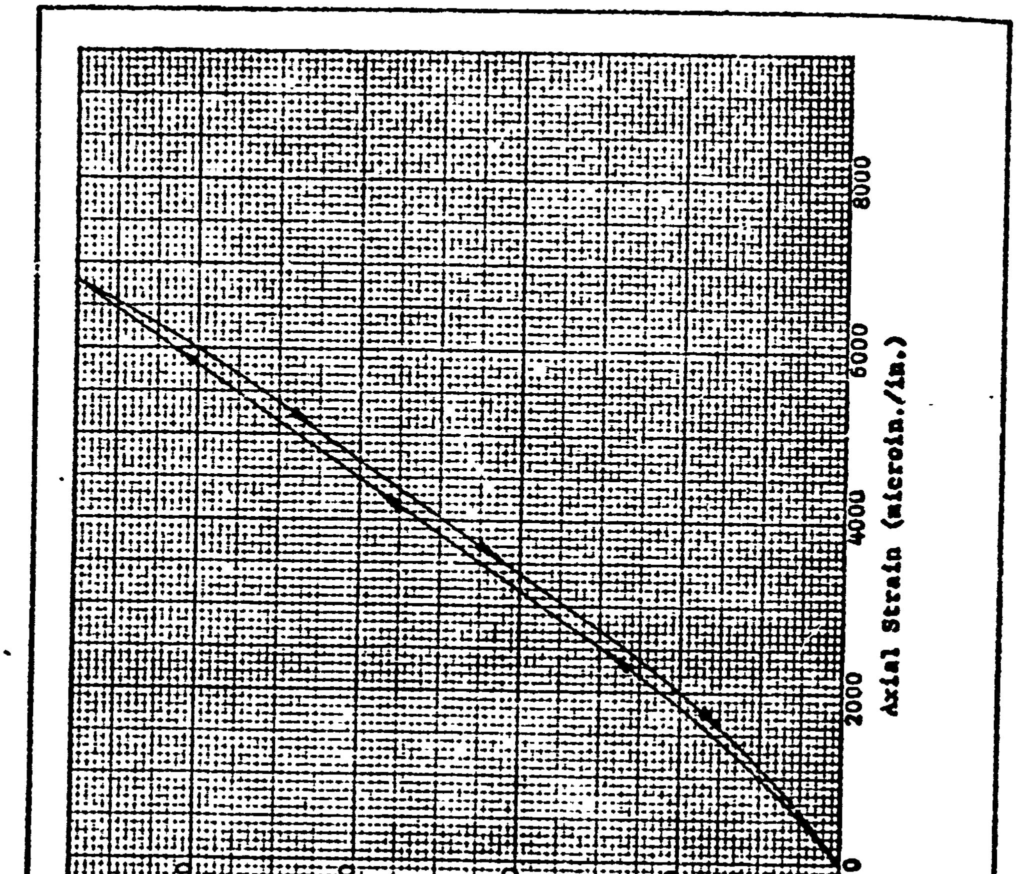
Posttest Photograph of Test Specimens

PLATE 18



CONFINED COMPRESSION TEST
CR-42 Core
Specimen 14a

PLATE 19



CONFINED COMPRESSION TEST
CR-42 Core
Specimen 16a

PLATE 20

APPENDIX I

DATA REPORT - HOLE CR-48 CORES

24 OCTOBER 1958

WARREN SITING AREA

Core No. 8 (Hole CR-48)

1. Fourteen pieces of core were received from the Warren area on 12 October 1968, designated CR-48 core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	27
A	2	28
A	3	29
A	4	30
B	5	95
B	6	96
B	7	97
B	8	98
C	9	182
C	10	183
C	11	184
C	12	185
C	13	186
C	14	187

2. The hole from which the core was taken was located in Larimer County, Colorado, township 12N, range 70W, section 20.

Warren Siting Area: Core No. 8 (Hole CR-48); Series I Tests

Results

Petrographic examination

3. About 15 ft of NX rock core in 14 pieces, representing three depths in hold CR-48, were received in October 1968 for testing. The petrographic sample is identified below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-10	8 (top portion)	98	1/3

4. All 14 pieces of core were similar in appearance except that the patches of black hornblende and biotite in the middle portion of piece 8 were smaller in size and more numerous than in the rest of the pieces.

5. The broken surfaces of the pieces of core appeared to represent fresh fractures associated with the drilling procedure rather than old fractures.

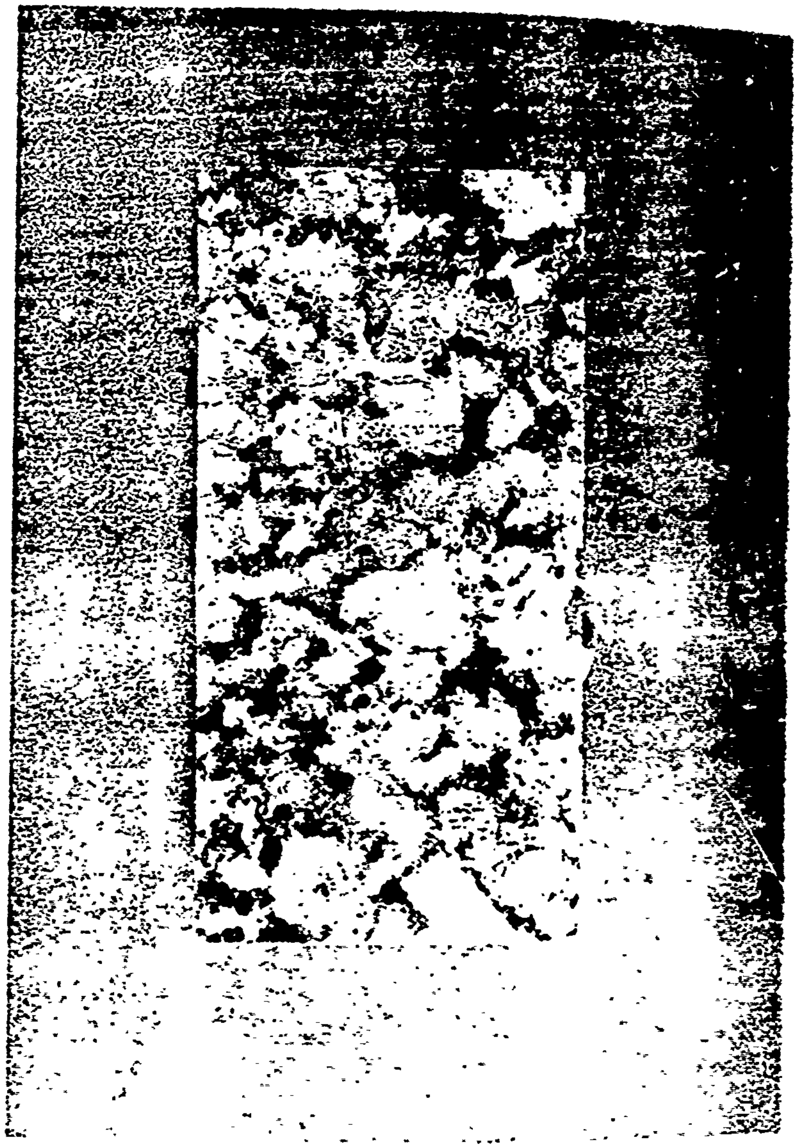
6. The test procedure was similar to that followed in examining the other samples of this series.

7. The rock in this core is coarse-grained, reddish granite (photograph 1) composed of pink microcline, white plagioclase feldspar, quartz, and biotite, with smaller amounts of hornblende, kaolinite, pyroxene, calcite, muscovite, and an opaque mineral. The plagioclase is either albite or oligoclase. There is some alteration of the feldspars, mainly of the plagioclase, to kaolinite.

8. Comparison with the reddish granite from core hole CR-42 indicates that the rock in the two cores is similar except that the CR-48 cores contain abundant biotite which was virtually absent in CR-42 cores. The CR-48 cores do not contain the limonite-coated fractures which were common in CR-42.

Schmidt number, specific gravity, porosity, and tensile strength

9. Three specimens from each depth interval were selected for the basic test. Due to the apparent uniform nature of the rock, only the three samples from the middle interval were subjected to all tests. Results are given below:



Photograph 1. Sawed surface of piece from core hole CR-48, depth 93 ft, natural size.

Warren Siting Area: Core No. 8 (Hole CR-48); Series I Tests

[illegible]	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
		Sample A - 30-ft Depth			
[illegible]	57.4	4.91	2.658	-	1065
[illegible]	57.3	4.96	2.658	-	1260
[illegible]	55.0	3.64	2.654	-	1360
[illegible]	56.5	4.50	2.657	-	1230
		Sample B - 95-ft Depth			
[illegible]	58.1	4.25	2.662	0.5	1205
[illegible]	59.3	3.64	2.674	0.0	1235
[illegible]	57.9	4.41	2.662	0.6	1080
[illegible]	58.4	4.10	2.666	0.4	1175
		Sample C - 185-ft Depth			
[illegible]	54.9	3.21	2.652	-	1295
[illegible]	57.9	3.43	2.663	-	1125
[illegible]	58.1	4.50	2.666	-	1185
[illegible]	57.0	3.71	2.664	-	1200

...ications are that the CR-48 core is a relatively uniform, moderately ...ense material of little porosity.

...ear tests

...0. Direct single plane shear tests were conducted on one sample ... each of the three depth intervals. Shear strengths of 1310, 1460, ... 1590 psi (average 1450 psi) were obtained on specimens 2c, 7c, and ... respectively. A posttest photograph of the test specimen is given ... Plate 1.

...nfined compressive strength tests

...1. Conventional unconfined compressive strength tests were conducted ... specimens from the upper and lower depth intervals and cyclic compressive ... on specimens from the middle depth interval. Results are given below:

Best Available Copy

Warren Siting Area: Core No. 8 (Hole CR-48); Series I Tests

Core No.	Depth, ft	Unconfined Compressive Strength, psi
1a	27	17,110
2b	28	20,170
4b	30	21,310
Avg	29	19,530
5a	95	21,300
6b	96	21,900
7a	97	23,000
Avg	96	22,070
10a	183	24,230
11a	184	23,030
13b	186	24,810
Avg	185	24,020

Only a slight change of strength is evident with depth, hardly sufficient to be of consequence in a material such as rock.

12. The specimens from the middle depth interval had two vertical and two horizontal electrical resistance strain gages affixed in order to measure strain during testing. Unloading cycles were made at 5000-psi intervals up to 15,000 psi. Stress-strain curves are given in plates 2, 3, and 4. The stress-strain relationships were linear almost to failure; hysteresis was negligible. To compute the deformation moduli, a tangent at 50 percent of the ultimate strength was constructed as a dashed line on the stress-strain curves. A posttest photograph of the test specimens, plate 5, shows the nature of failure, steep sided coning.

Moduli of deformation

13. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on sample No. 8 by the dynamic (fundamental frequency) method and on the unconfined compressive strength specimens statically at approximately 50 percent of the ultimate strength. Results are given below:

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
8	9.81	4.21	4.95	0.17

(Continued)

(Continued)

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Statically		
5a	9.90	3.93	6.88	0.26
6b	9.80	3.83	7.42	0.28
7a	9.40	3.76	6.27	0.25

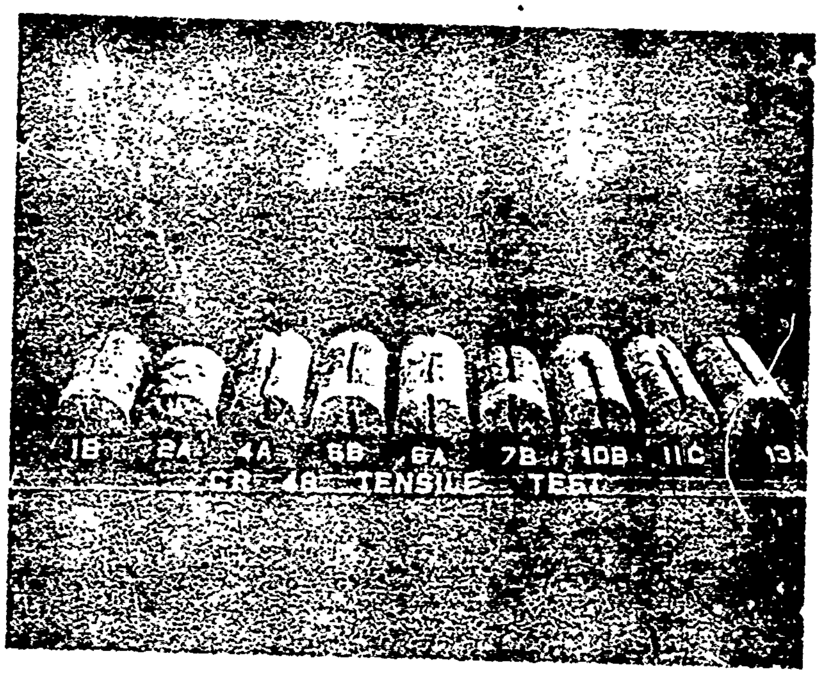
Velocity measurements

14. The compressional wave velocity was determined directly as the sonic propagation velocity on specimen No. 3 to be 18,260 fps. The shear wave velocity was determined from the torsional frequency obtained in the moduli determinations to be 10,885 fps, 60 percent of the compressional velocity.

Conclusions

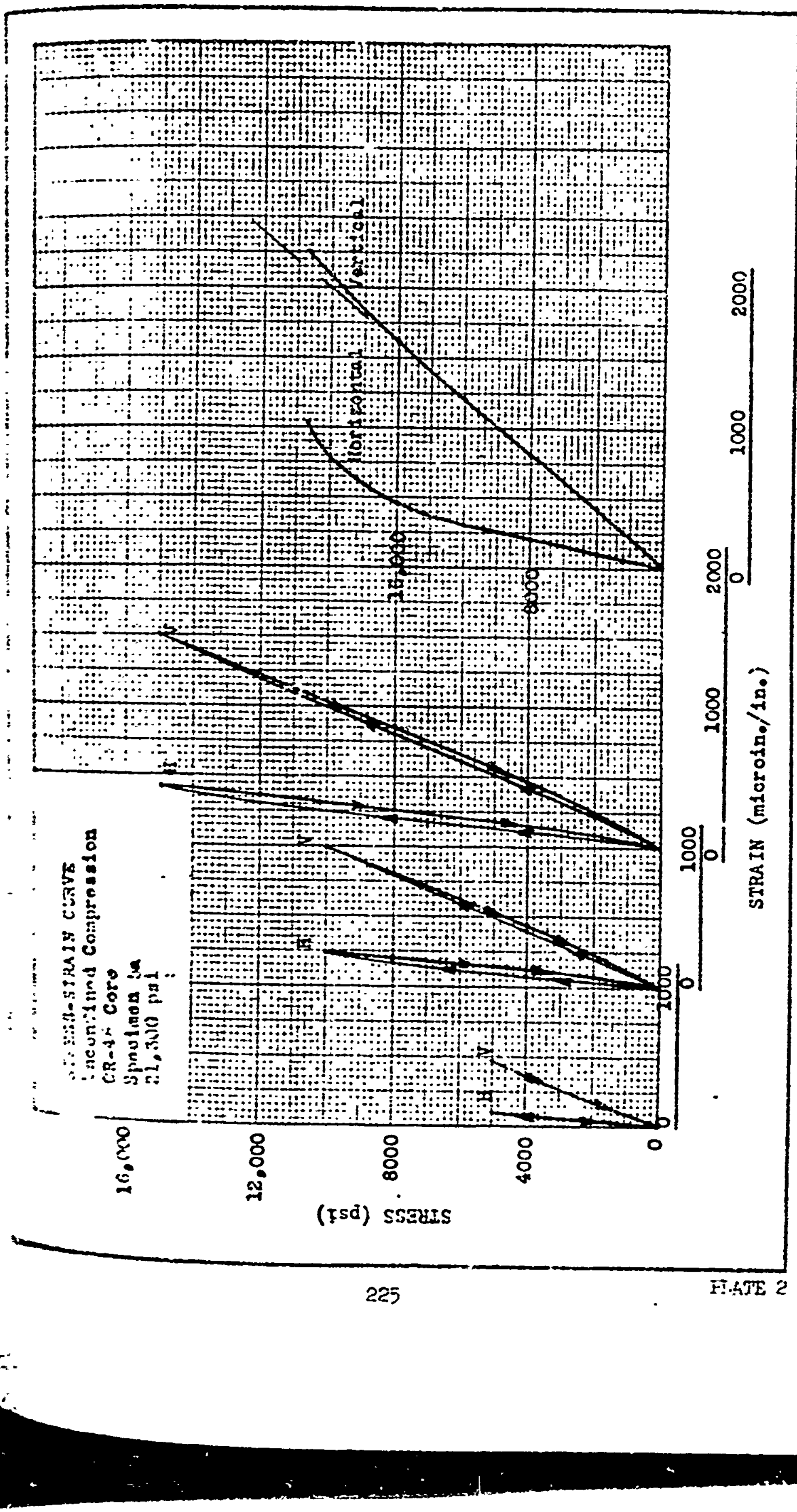
15. The CR-48 core is identified as a coarse-grained, reddish granite similar to the core from hole CR-42 except that the CR-48 cores contain abundant biotite which was virtually absent in CR-42 cores. The core is relatively uniform with depth, although not as uniform as the core from hole CR-39. Consensus results of physical properties are:

Property	Result
Specific gravity	2.65
Percent porosity	0.4
Compressive strength, psi	21,870
Tensile strength, psi	1,200
Young's modulus, psi x 10^6	9.7
Compressional wave velocity, fps	18,260



Posttest Photographs

PLATE 1



Unconfined Compression
Core
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
2000
Horizontal
Vertical

PLATE 2

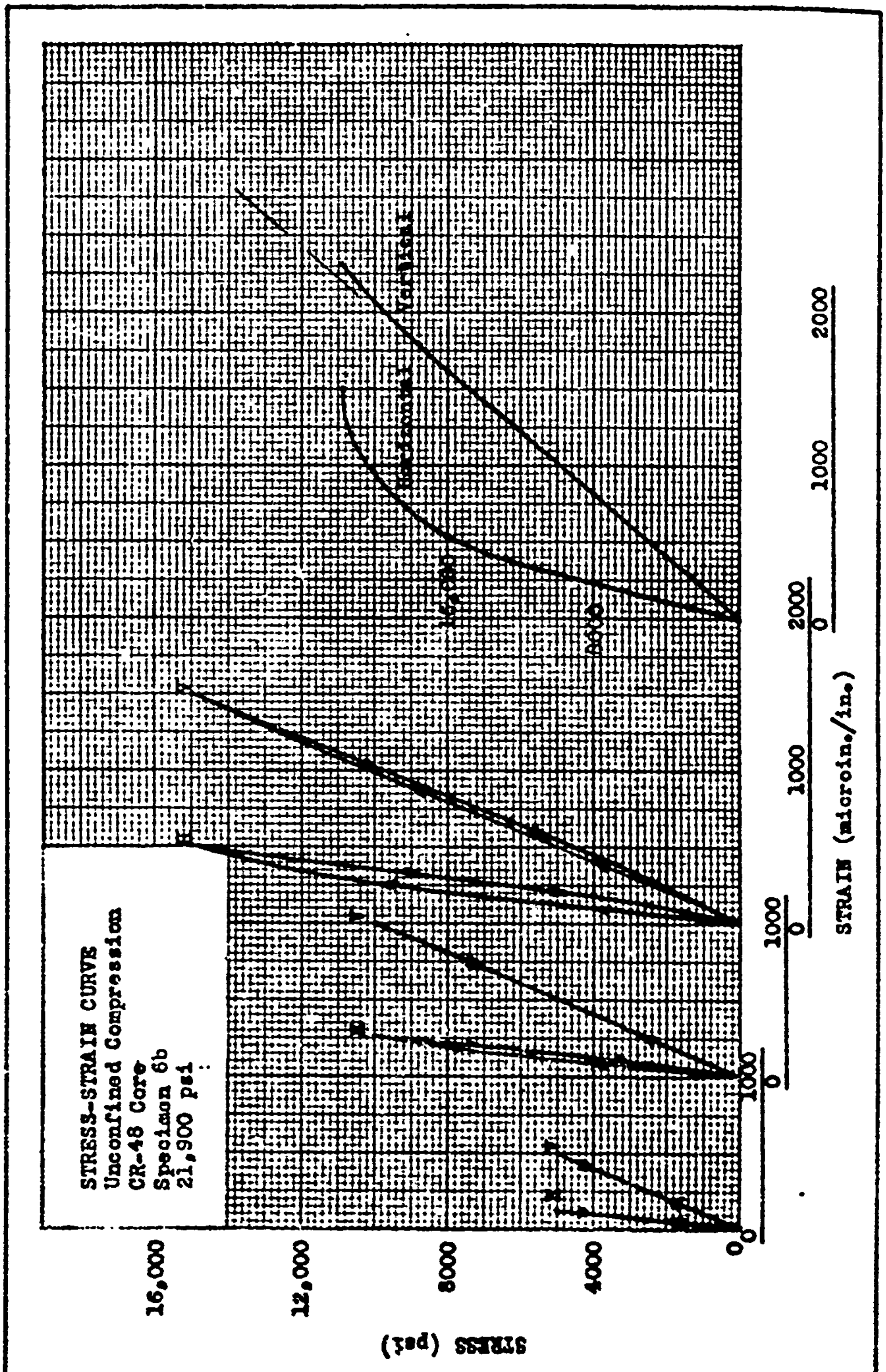

STRESS-STRAIN CURVE
Unconfined Compression
CR-48 Core
Specimen 6b
21,900 psi
STRESS (psi)
16,000
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
0
1000
2000
0
1000
2000
0
1000
2000

PLATE 3

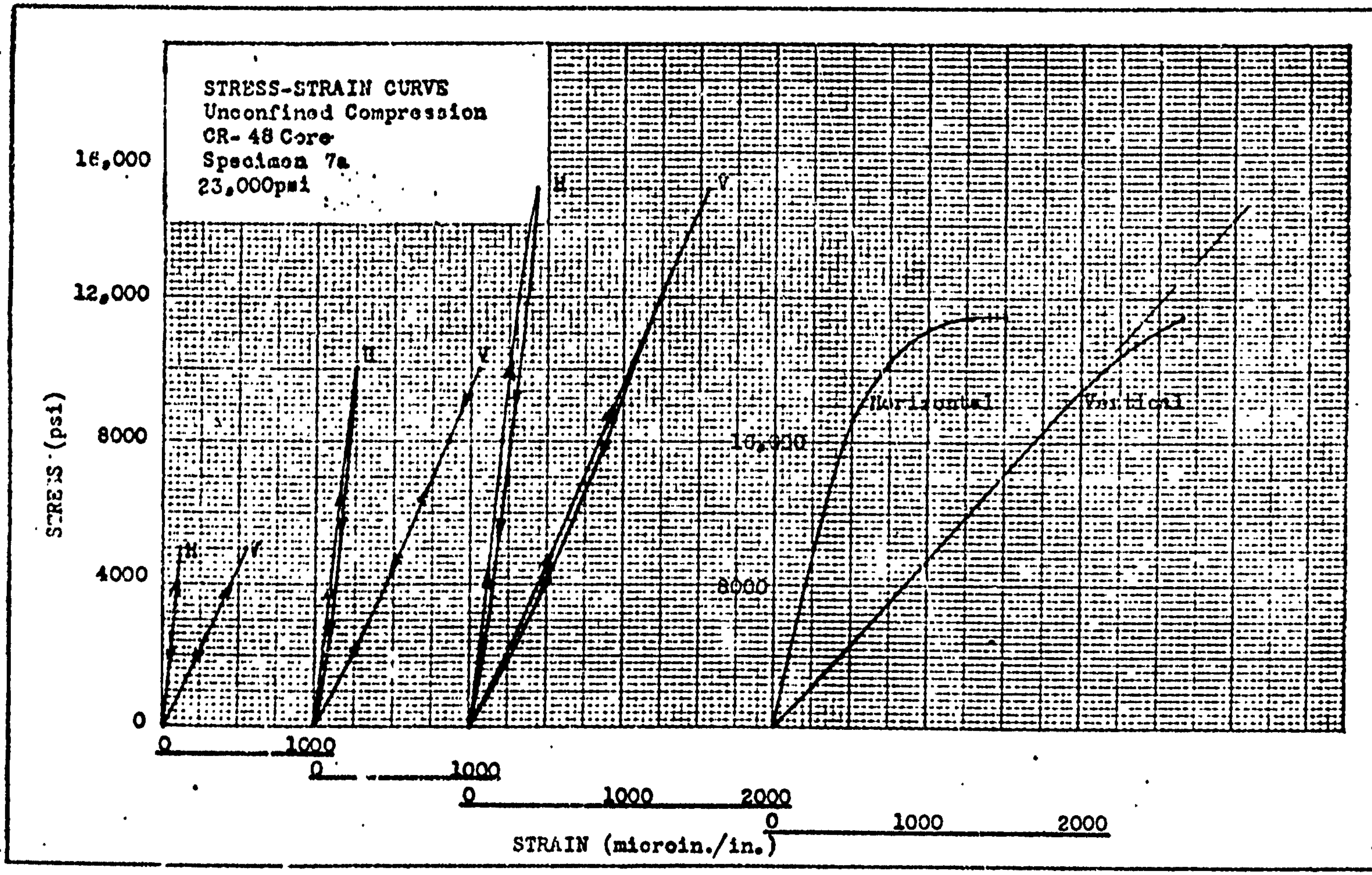
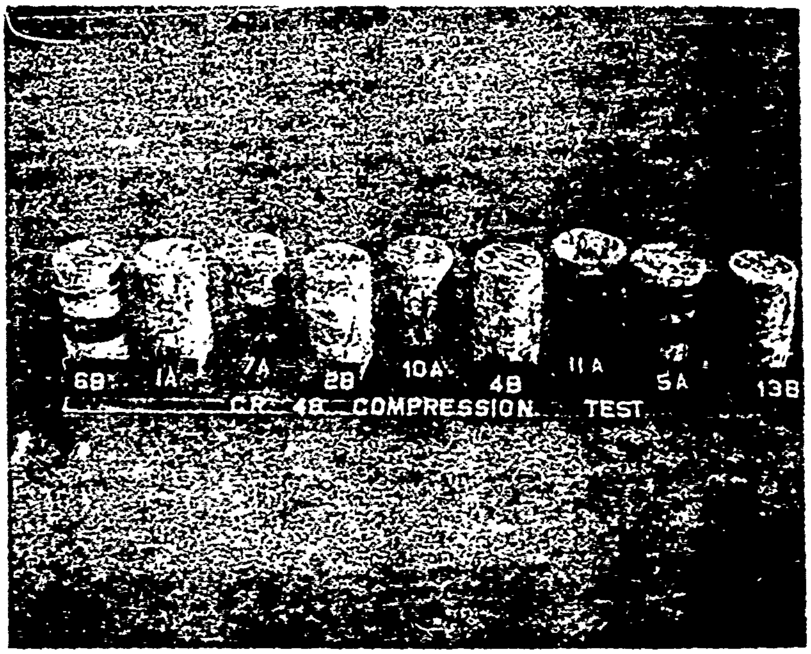

STRESS-STRAIN CURVE
Unconfined Compression
CR- 48 Core
Specimen 7a
23,000psi
STRESS (psi)
16,000
12,000
8000
4000
0
H
V
10,000
8000
Horizontal
Vertical
0
1000
2000
STRAIN (microin./in.)

PLATE 4



Posttest Photograph

PLATE 5

APPENDIX J

DATA REPORT - HOLE CR-10 CORES

23 OCTOBER 1958

Core No. 7 (Hole CR-10)

1. Thirteen pieces of core were received from the Warren area on 7 October 1958, designated CR-10 core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	28
A	2	29
A	3	56
A	4	59
B	5	140
B	6	141
B	7	143
B	8	144
C	9	190
C	10	191
C	11	192
C	12	194
C	13	196

2. The hole from which the core was taken was located in Albany County, Wyoming, township 24N, range 73W, section 14.

Results

Petrographic examination

3. About 15 ft of NX rock core from three depths in hole CR-10 were received 7 October 1968 for testing. The petrographic sample is described below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-5	8 (top portion)	143	1/3

4. The test procedure was similar to that used for previous samples in this series.

5. The two pieces of core representing depths between 27.9-29.9 ft were white pegmatite like that shown in the central portion of photograph 1. All of the other 11 pieces were more like the top and bottom parts of the core length shown in photograph 1.

6. The piece of core shown in photograph 1 is not a typical length of core, but it does have the advantage of showing the extremes of appearance in one piece of core. The black rock at each end of this piece is typical of most of the rock in this core. However, alternations in composition and appearance as evidenced by photograph 1 are common in rocks of this type.

7. The core was logged in the field as gneiss, and this is a suitable designation for this rock. Gneiss is the rock name for a metamorphic rock that shows alternating layers of light and dark colored minerals. This was originally an igneous rock, probably a tonalite.

8. The typical black gneiss in this core is composed of quartz, plagioclase feldspar, and biotite with much smaller amounts of amphibole (colorless), microcline, and kaolinite. The plagioclase is albite or oligoclase and is not much altered to clay or sericite.

9. The white pegmatite contains the same minerals as the black gneiss but in different amounts. There is less biotite and more quartz and microcline in the white rock than in the black material.

10. All of the rock is medium grained and fairly equigranular with little development of crystal outline by individual grains.

Photograph 1. Sawed surface of piece 8 (top portion) from core hole CR-10, depth 143 ft, natural size. The dark part of the core is typical of most of the rock in the whole core while the white portion typifies small areas of pegmatite.

Warren Siting Area: Core No. 7 (Hole CR-10); Series I Tests

Schmidt number, specific gravity, porosity, and tensile strength

11. Three specimens from each depth interval were selected for the basic tests. Results are given below:

Core	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
			Sample A - 30-ft Depth		
1b	58.9	5.03	2.635	0.0	1290
2a	55.7	4.45	2.633	0.4	1435
2c	*	*	2.627	0.9	*
Avg	57.3	4.74	2.632	0.4	1360
			Sample B - 140-ft Depth		
6a	52.5	3.87	2.753	0.0	850
7a	54.7	3.97	2.724	0.0	1140
9b	56.7	4.55	2.712	0.6	1225
Avg	54.6	4.15	2.730	0.2	1070
			Sample C - 195-ft Depth		
10b	54.8	4.63	2.752	0.4	1160
12c	55.0	3.76	2.722	0.7	975
13c	52.9	4.04	2.744	1.1	800
Avg	54.2	4.14	2.739	0.7	980

* Specimen too short to test.

12. The light-colored gneiss from the upper elevation is not as dense as the other material, but has a higher rebound number and tensile strength. This may be explained by the foliation in samples from the lower elevations which could be expected to result in lower strength indications.

Shear tests

13. Direct single plane shear tests were conducted on three samples of the foliated gneiss. Shear strengths of 1370, 1220, and 1540 psi (average 1370) were obtained on samples 6d, 8c, and 12a, respectively. A posttest photograph of the specimens is given in plate 1.

Unconfined compressive strength tests

14. Conventional unconfined compressive strength tests were conducted on specimens from the upper and lower depth intervals and cyclic compressive tests on specimens from the middle depth interval. Results are given below:

Core No.	Depth, ft	Unconfined Compressive Strength, psi
1a	28	28,000
1c	28	30,700
2b	29	31,100
Avg	28	29,930
5a	140	16,800
5c	141	12,100
8a	144	23,100
Avg	142	17,330
9a	190	12,000
10a	191	14,300
13b	195	13,500
Avg	192	13,270

15. All specimens had two vertical and two horizontal electrical resistance gages affixed in order to monitor strain during loading. Unloading cycles were made at 5000 and 10,000 psi on the cyclic tests. Stress-strain curves are given in plates 2-10. The hysteresis loops were small and closed. A posttest photograph of the test specimens, plate 11, shows the nature of failure, steep sided coning, prevalent in the more solid specimens from the upper elevation. The foliated specimens failed along the bands of dissimilar material in most every case; thus, the lower indicated strengths for the lower elevations.

Moduli of deformation

16. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on three samples by the dynamic (fundamental frequency) method and on the unconfined compressive strength specimens statically at approximately 50 percent of the ultimate strength. Results are given below:

Warren Siting Area: Core No. 7 (Hole CR-10); Series I Tests

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
2	6.87	3.10	2.94	0.11
8	9.88	4.30	4.70	0.15
13	10.08	4.20	5.60	0.20
		Statically		
1a	8.80	3.66	4.88	0.20
1c	8.77	3.68	4.72	0.19
2b	8.81	3.64	5.06	0.21
5a	9.33	3.73	6.22	0.25
6c	9.37	3.47	10.41	0.35
8a	10.00	4.07	6.17	0.23
9a	8.57	3.17	9.52	0.35
10a	9.00	3.78	4.84	0.19
13b	9.72	3.86	6.75	0.26
Avg Static	9.15	3.67	6.51	0.25

17. The Young's and shear moduli are relatively consistent between the solid and foliated material. However, the Poisson's ratio for the foliated rock (samples 5a through 13b) is quite variable which results in high variability of the bulk modulus.

Velocity measurements

18. The compressional wave velocity was determined directly as the sonic propagation velocity, and the shear wave velocity was determined from the torsional frequency obtained in the moduli determinations.

Core No.	Compressional Velocity, fps	Shear Velocity, fps
2	15,590	9,415
8	17,890	10,915
13	18,225	10,835
Avg	17,240	10,390

The shear velocity is approximately 60 percent of the compressional velocity.

Conclusions

19. The CR-10 core is identified as a gneiss. The light-colored material (here from the upper elevation) is significantly different from the foliated rock. The lower strength of foliated rock is due to the nature of failure--along the bands of dissimilar material.

Property	Light Colored	Foliated
Specific gravity	2.63	2.73
Percent porosity	0.4	0.4
Compressive strength, psi	29,930	15,300
Tensile strength, psi	1,360	1,025
Young's modulus, psi x 10^6	8.8	9.3
Compressional wave velocity, fps	15,590	18,060

Results

Hydrostatic compression

20. Hydrostatic compressive tests were conducted on three specimens, one each to pressures of 9000, 18,000, and 36,000 psi. The specimens were prepared in a manner similar to the unconfined compressive tests except that the test at 36,000 psi was conducted on a 1.5-in.-diameter specimen recored from the NX size cores so as to have sufficient axial load capacity to fracture the specimens. Some difficulty was experienced with the gages on the specimen tested to 36,000 psi. Utilizing the results of loading cycles 3 and 4, the bulk modulus, K , was computed from the relation:

$$K = \frac{\sigma}{\epsilon_1 + \epsilon_2 + \epsilon_3}$$

where:

σ = hydrostatic stress

ϵ_1 = vertical strain

$\epsilon_2 = \epsilon_3$ = horizontal strain

21. Information for the specimens is given below:

Specimen No.	Maximum Stress, psi	Stress-Strain Curves in Plates	Bulk Modulus K, psi
[illegible]	9,000	12, 13	6.33
5b	18,000	14, 15	7.43
[illegible]	36,000	16, 17	7.22 (at 18,000 psi)

Specimens 6b and 6d strained almost equally in the two mutually perpendicular directions; however, inisotropy is indicated in specimen 5b by the unequal strains measured in the two different directions. However, the total strain in all three directions for the two specimens tested to [illegible] psi is approximately equal. This, of course, is the significance of the bulk modulus, i.e., the three mutually perpendicular strains may vary [illegible], but, when combined, they yield a bulk modulus comparable to a specimen which has strained equally in all directions. The moduli are comparable to those obtained in the Series I tests.

Warren Siting Area: Core No. 3 (CR-10); Series II Tests

Triaxial compression

22. Triaxial tests were conducted on the same specimens utilized for the hydrostatic tests at confining pressures equal to the hydrostatic pressures previously applied. Stress-strain curves are given in plates 18, 19, and 20. The maximum deviator stress, Young's modulus, computed as the initial tangent, and Poisson's ratio are given below:

Specimen No.	Confining Stress, psi	Deviator Stress, psi	Young's Modulus psi x 10^6	Poisson's Ratio
6b	9,000	58,000	13.0	0.25
5b	18,000	90,000	12.0	0.23
6d	36,000	106,000	11.0	0.21

Young's moduli determined on the triaxial tests are apparently somewhat higher than the moduli previously determined on the unconfined tests. Possibly the lateral pressure in the triaxial tests reduces the tendency of the bedding planes to move under load, resulting in less strain and, hence, higher moduli.

23. The Mohr's circles for all tests are given in plate 21. An initial angle of shearing resistance of approximately 45 deg is indicated. However, the failure envelope develops a pronounced curvature above 9000 psi confining pressure and appears to be approaching linearity at 36,000 psi confining pressure. Discretion must be used in interpreting the results of the triaxial test for the CR-10 core. The stratified nature of the rock violates the first requirement for a triaxial test, homogeneity of the test specimen. Therefore, the apparent approaching linearity of the envelope should not be considered the yield limit of the rock in the Von Mises tradition, but probably is a result of the bedding and stratification.

24. The compressional wave velocity was recorded during test to failure of two specimens, 5b and 6b. Equipment malfunction prevented measurements during test of specimen 6d. Results are given below:

Specimen 5b		Specimen 6b	
Axial Stress, psi	Wave Velocity, fps	Axial Stress, psi	Wave Velocity, fps
0	17,000	0	18,000
9,000 (Hydrostatic)	18,570	18,000 (Hydrostatic)	19,500
20,000	19,000	20,000	20,000
30,000	21,000	40,000	20,700
40,000	22,500	60,000	23,400
50,000	23,700	80,000	25,000
60,000	24,500	90,000	25,000

Considerable difficulty was experienced in obtaining a valid wave picture, however, indications are that the velocity does change somewhat under stress. A posttest photograph of the test specimens is given in plate 22.

Confined compression

25. Confined compression tests were conducted on two specimens, 6e and 12b, prepared essentially as the triaxial test specimens. Confining pressure was applied to prevent lateral straining as axial load was applied by the piston. Therefore, a pseudo one-dimensional state of stress was induced, from which can be computed a constrained modulus. The axial stress-strain curves are given in plates 23 and 24. The lateral stress required to maintain a condition of no lateral strain is given on the far left of the curves.

26. The constrained modulus, M_c , may be computed from:

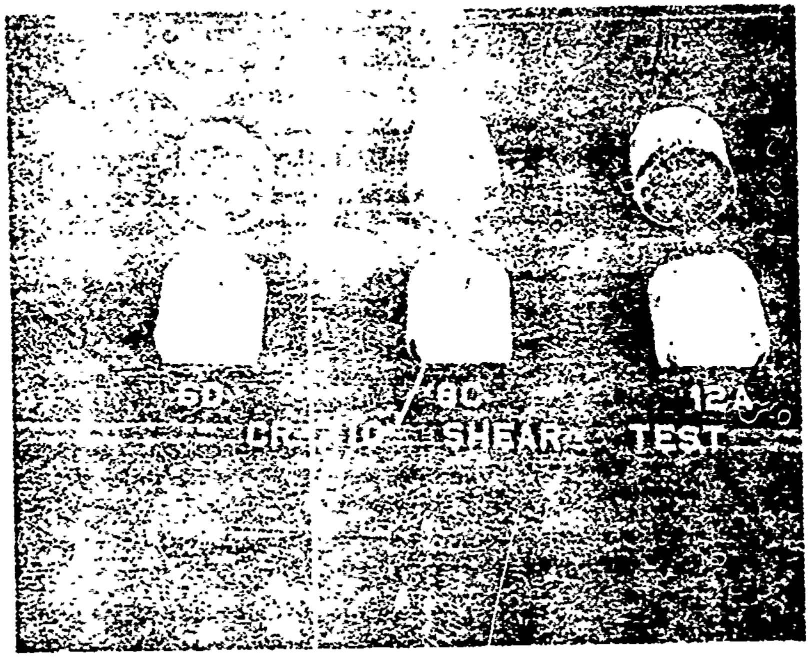
$$M_c = \frac{E\ (1-u)}{(1+u)(1-2u)}$$

where:

E = Young's modulus

u = Poisson's ratio

Using the average results from the triaxial tests ($E = 12.0 \times 10^5$ psi; $u = 0.23$), the constrained modulus is computed to be 13.9×10^5 psi. The constrained modulus computed as a tangent at the midpoint of the stress-strain curves for specimens 6e and 12b is approximately 15.0×10^5 psi for both specimens. Reasonably good agreement is, therefore, indicated between the theoretical and experimental results. Significantly, the stress-strain curves for this rock are nonlinear at the 30,000 psi lateral pressure level as were those for the soda diorite from the Laramie area. The CR-42 material, however, developed a linear stress-strain relationship at higher lateral pressure.



Posttest Photographs

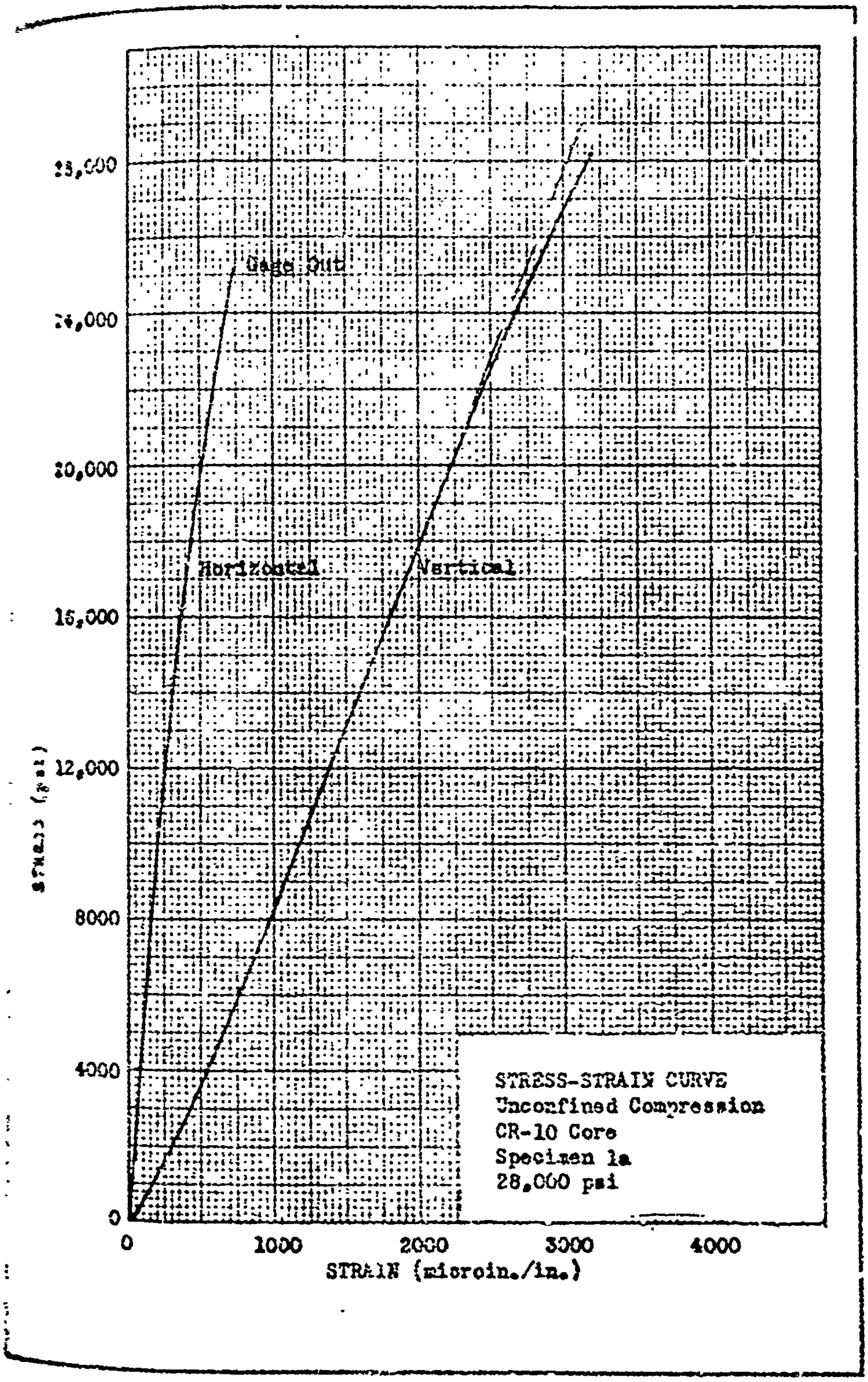

28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
Gage Out
Horizontal
Vertical
0
1000
2000
3000
4000
STRAIN (microin./in.)
STRESS-STRAIN CURVE
Unconfined Compression
CR-10 Core
Specimen 1a
28,000 psi

PLATE 2

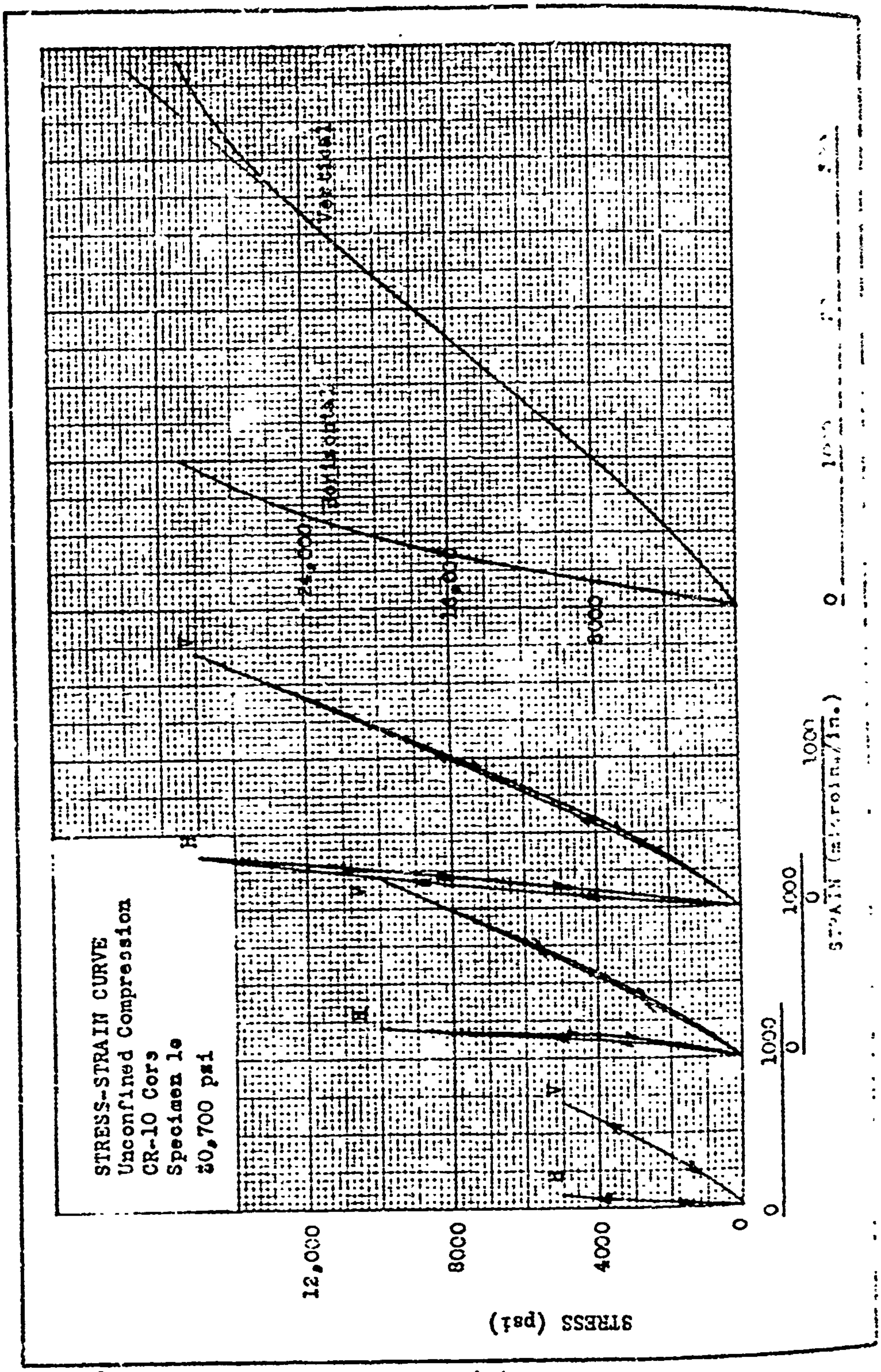

STRESS-STRAIN CURVE
Unconfined Compression
CR-10 Core
Specimen 1e
30,700 psi
STRESS (psi)
12,000
8000
4000
0
0
1000
0
1000
0
1000
0
STRAIN (microin./in.)
H
V
H
V
H
V
8000
16,000
24,000

PLATE 3

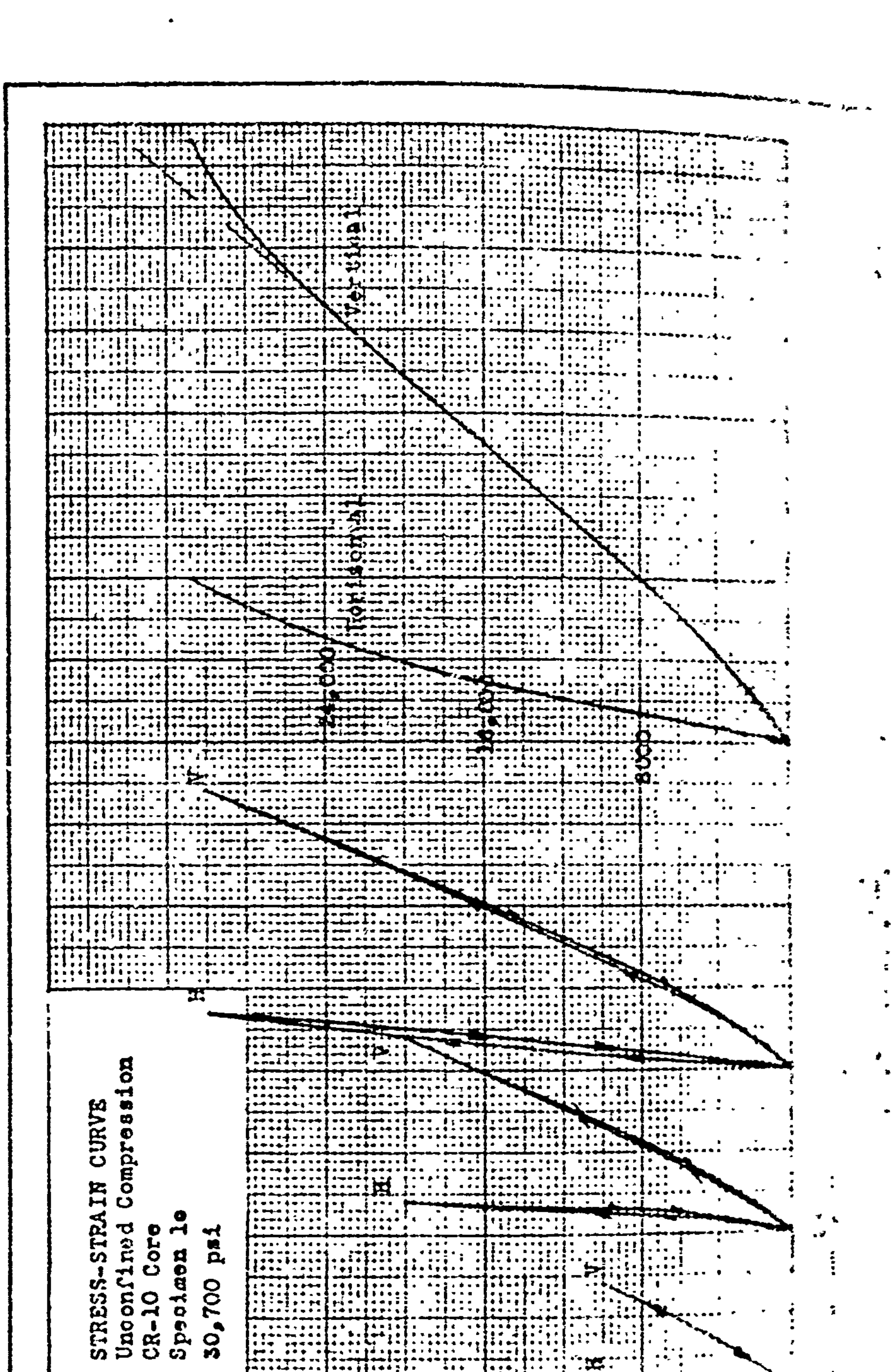
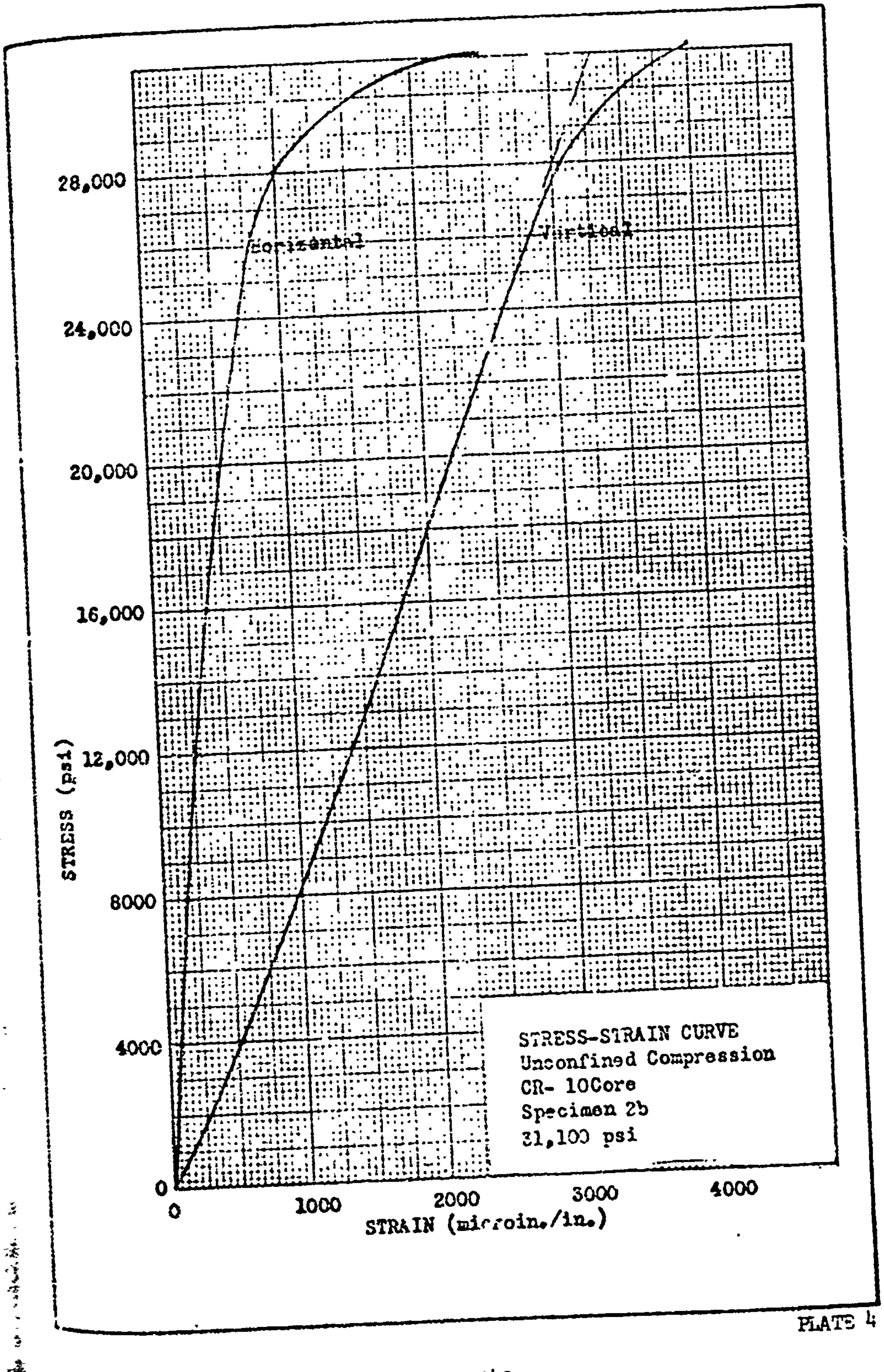

STRESS-STRAIN CURVE
Unconfined Compression
CR-10 Core
Specimen 1e
30,700 psi
STRESS (psi)
12,000
8000
4000
0
24,000
16,000
8000
Horizontal
Vertical
H
V

PLATE 3



28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
Horizontal
Vertical
0
1000
2000
3000
4000
STRAIN (microin./in.)
STRESS-STRAIN CURVE
Unconfined Compression
CR- 10Core
Specimen 2b
31,100 psi

PLATE 4

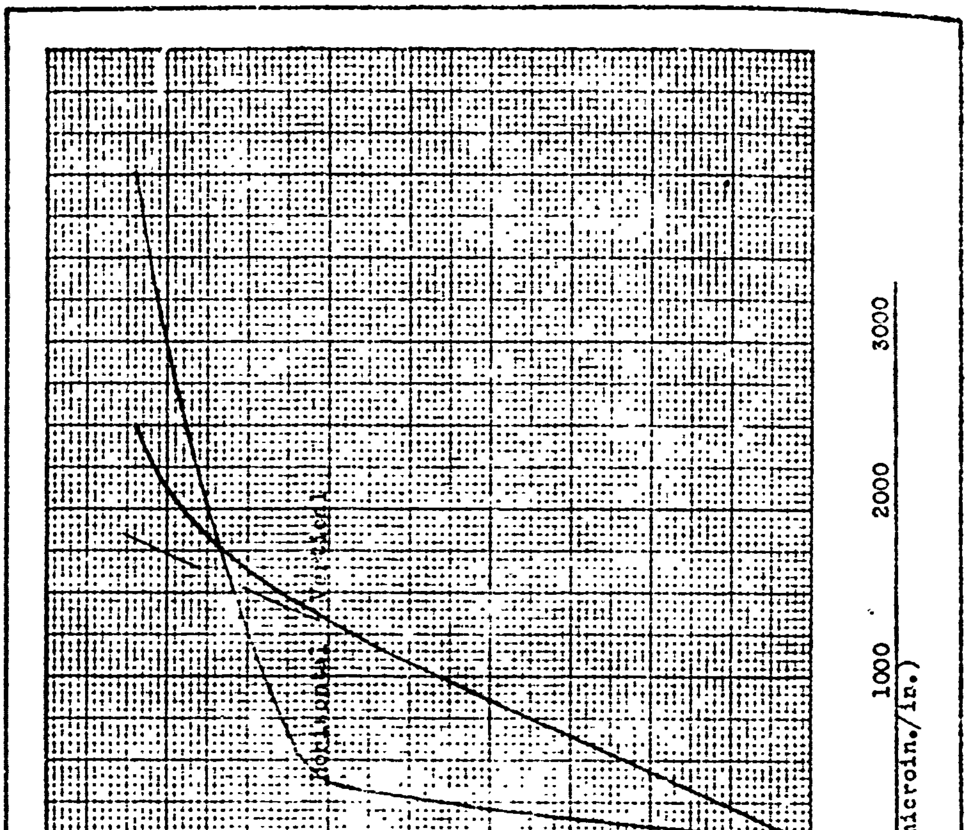

STRESS-STRAIN CURVE
Unconfined Compression
CR- 10 Core
Specimen 5a
16,800 psi
STRESS (psi)
STRAIN (microin./in.)
Horizontal
Vertical
0
4000
8000
12,000
1000
2000
3000

PLATE 5

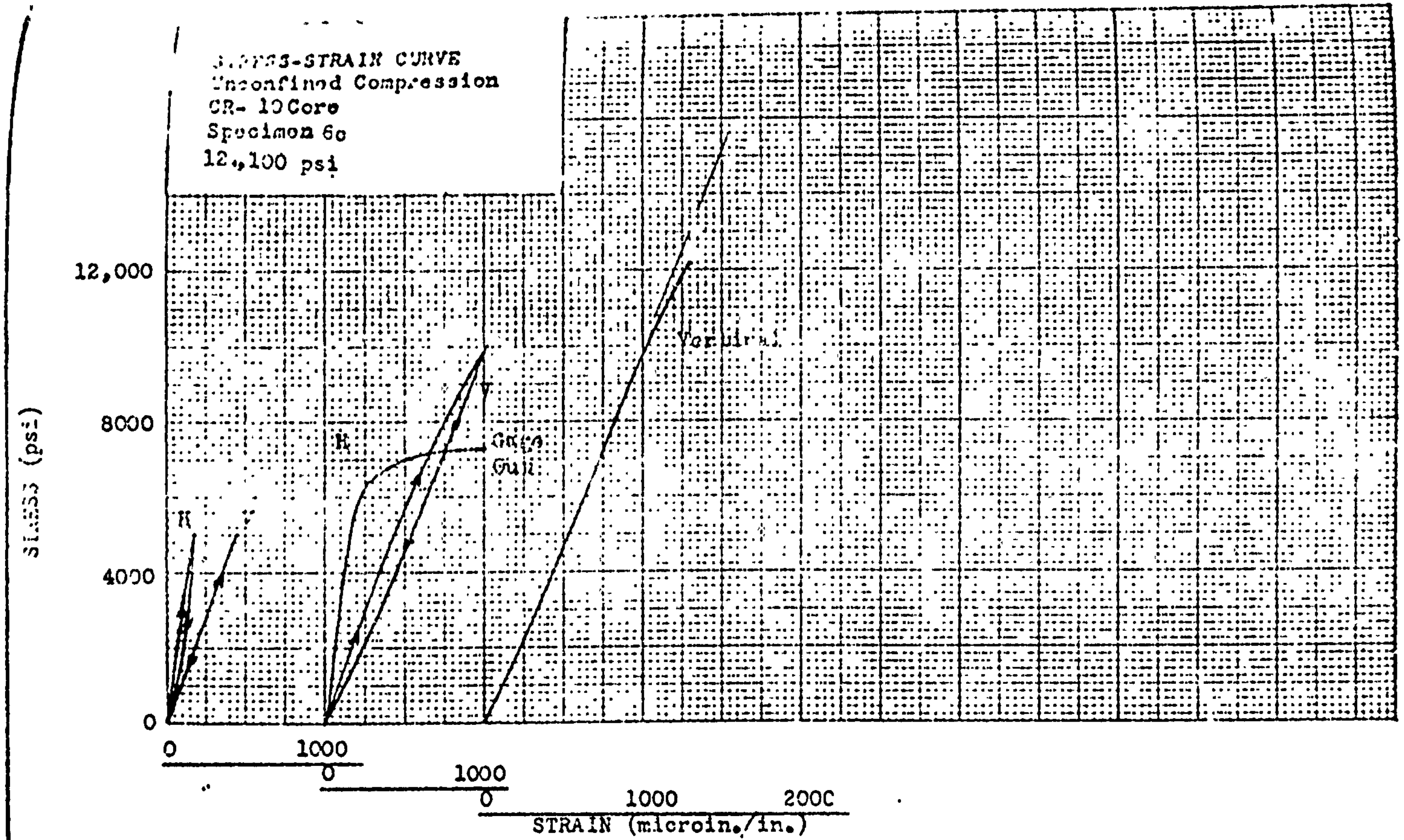

STRESS-STRAIN CURVE
Unconfined Compression
CR- 10 Core
Specimen 6c
12,100 psi
12,000
8000
4000
0
STRESS (psi)
H
V
Gage Fail
Vertical
1000
2000
STRAIN (microin./in.)

PLATE 6

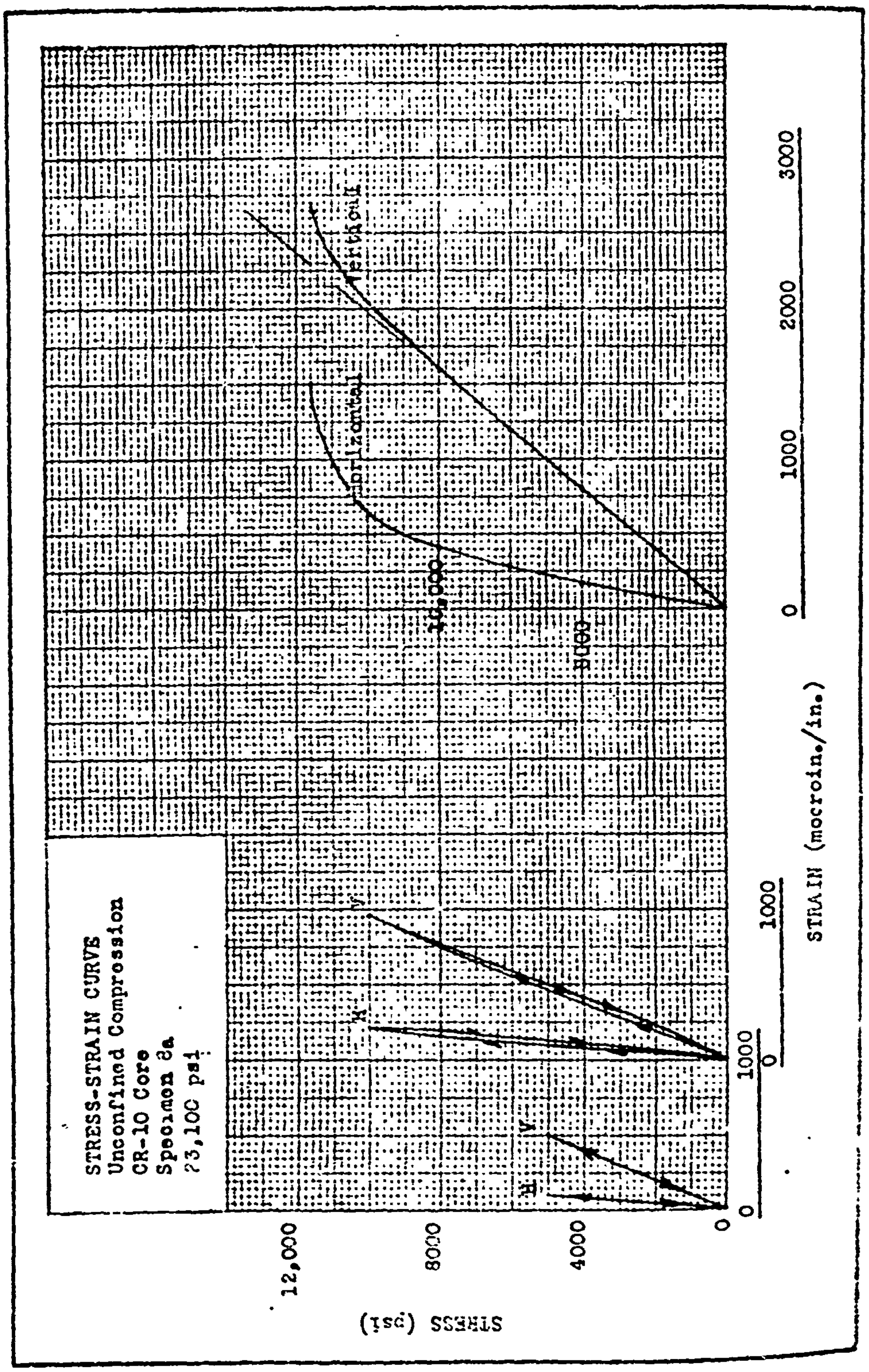
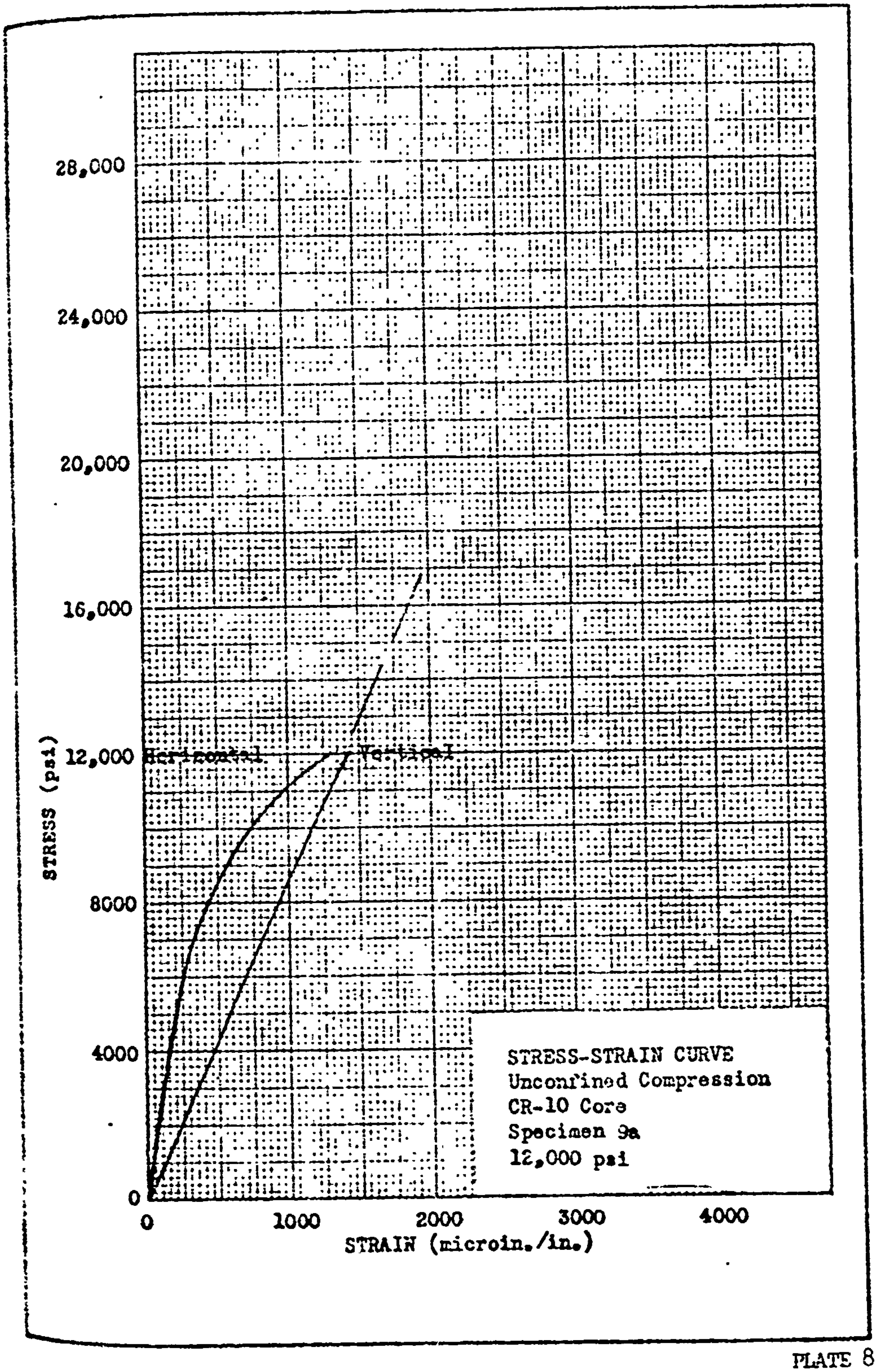

STRESS-STRAIN CURVE
Unconfined Compression
CR-10 Core
Specimen 8a
23,100 psi
STRESS (psi)
STRAIN (mocroin./in.)
12,000
8000
4000
0
1000
2000
3000
H
V
Horizontal
Vertical
10,000
8000

PLATE 7



28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
Horizontal
Vertical
0
1000
2000
3000
4000
STRAIN (microin./in.)
STRESS-STRAIN CURVE
Unconfined Compression
CR-10 Core
Specimen 9a
12,000 psi

PLATE 8

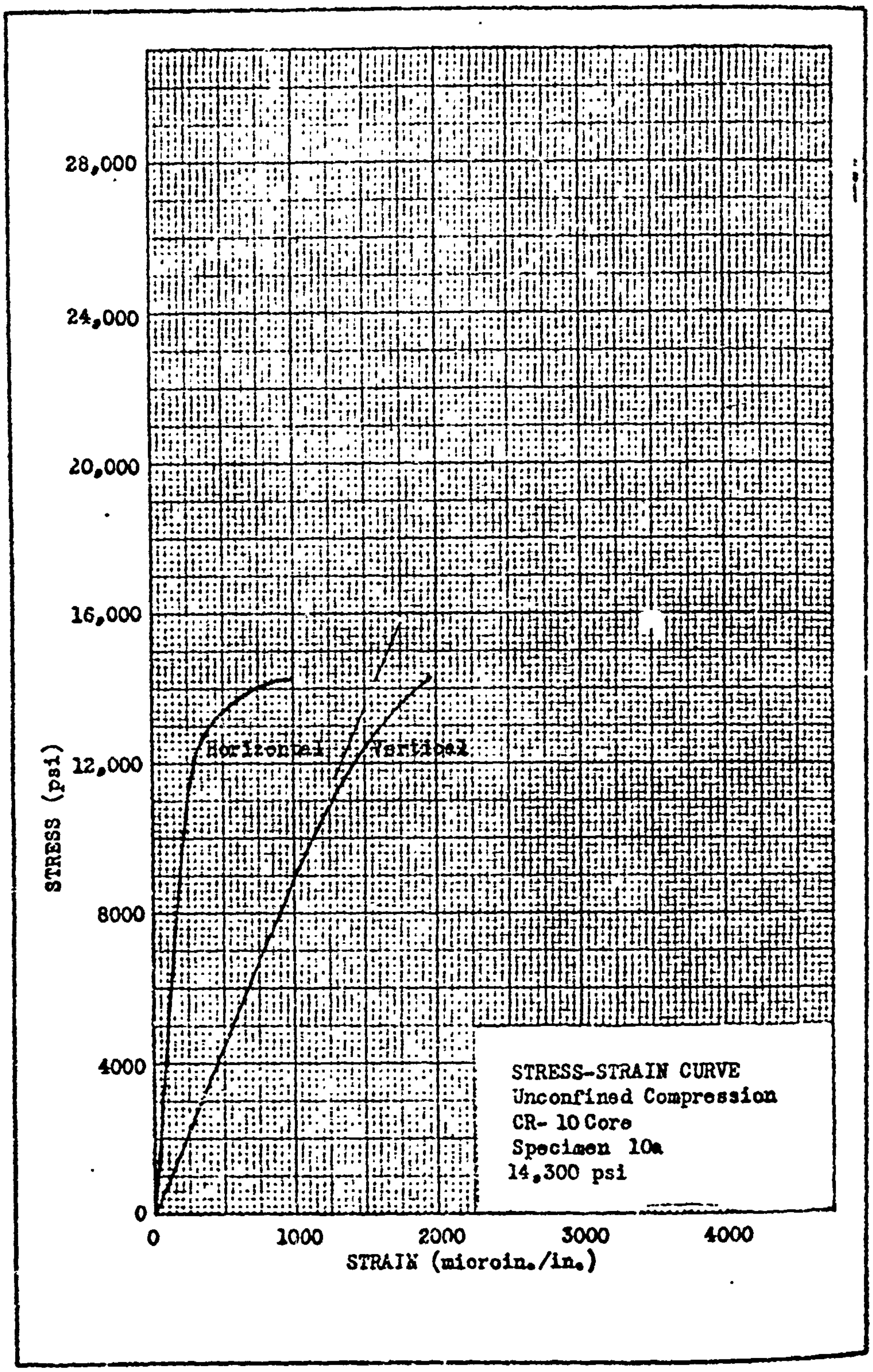

28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR- 10 Core
Specimen 10a
14,300 psi
0
1000
2000
3000
4000
STRAIN (microin./in.)

PLATE 9

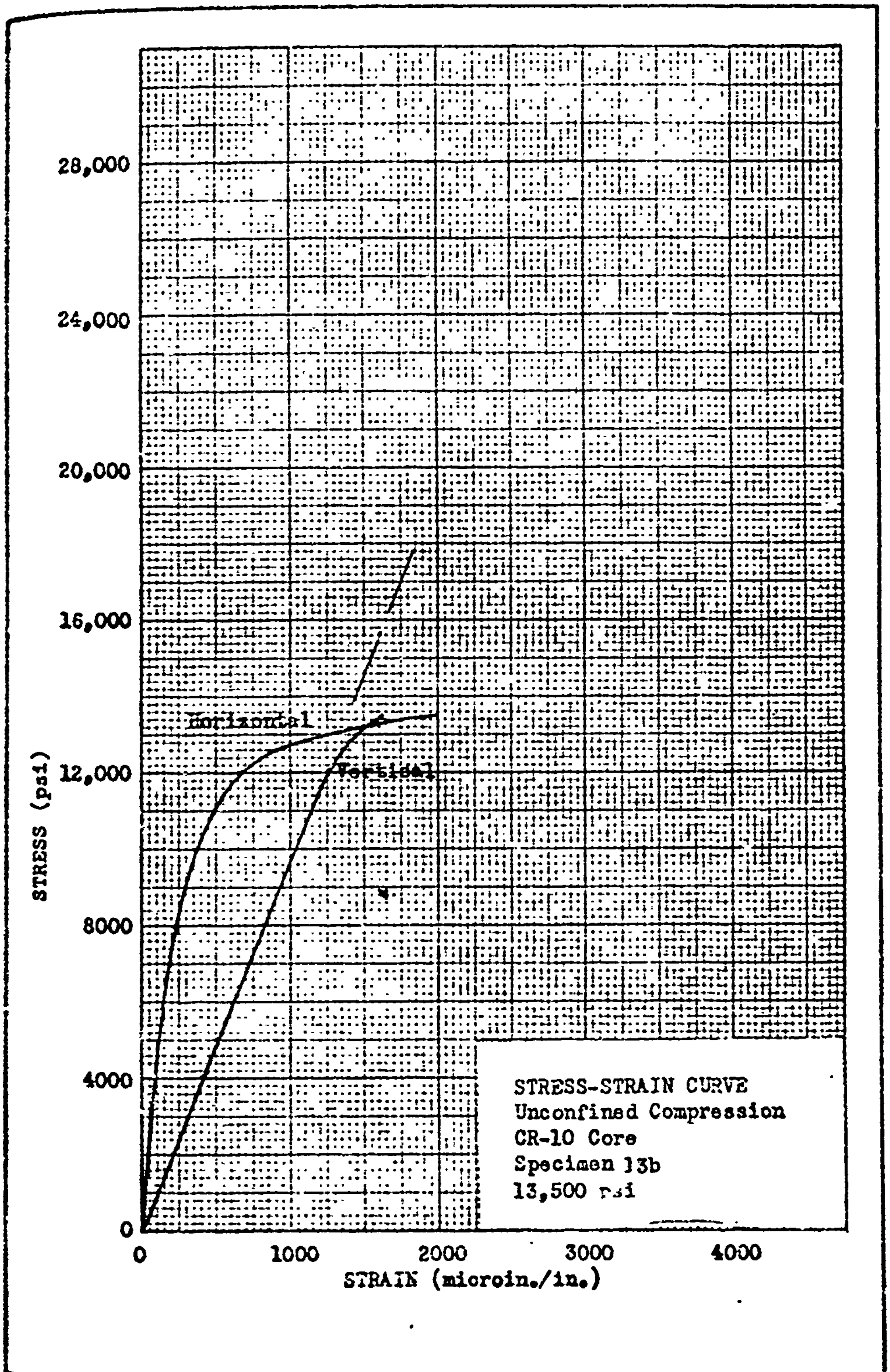
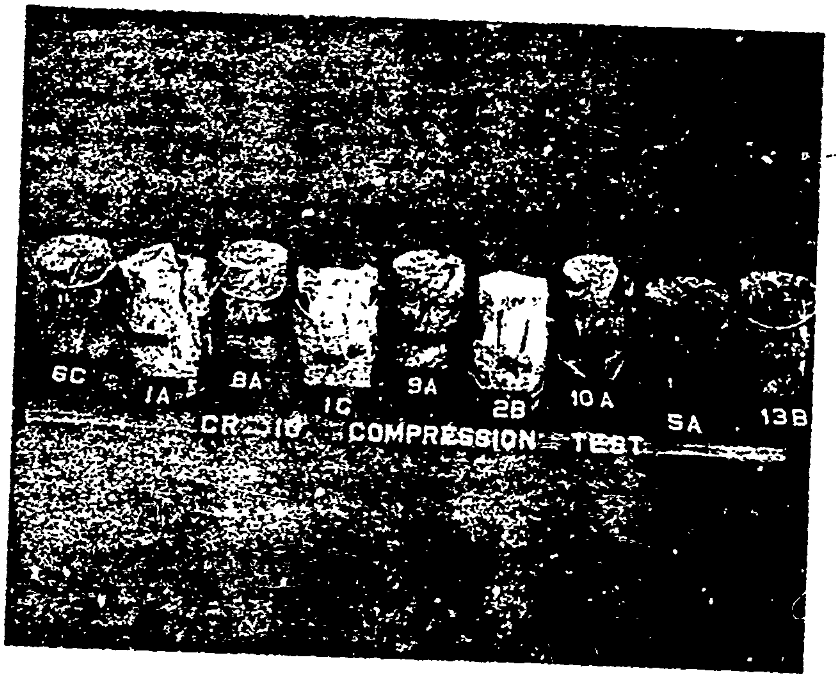

28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
4000
STRAIN (microin./in.)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR-10 Core
Specimen 13b
13,500 psi

PLATE 10



Posttest Photograph

PLATE 11

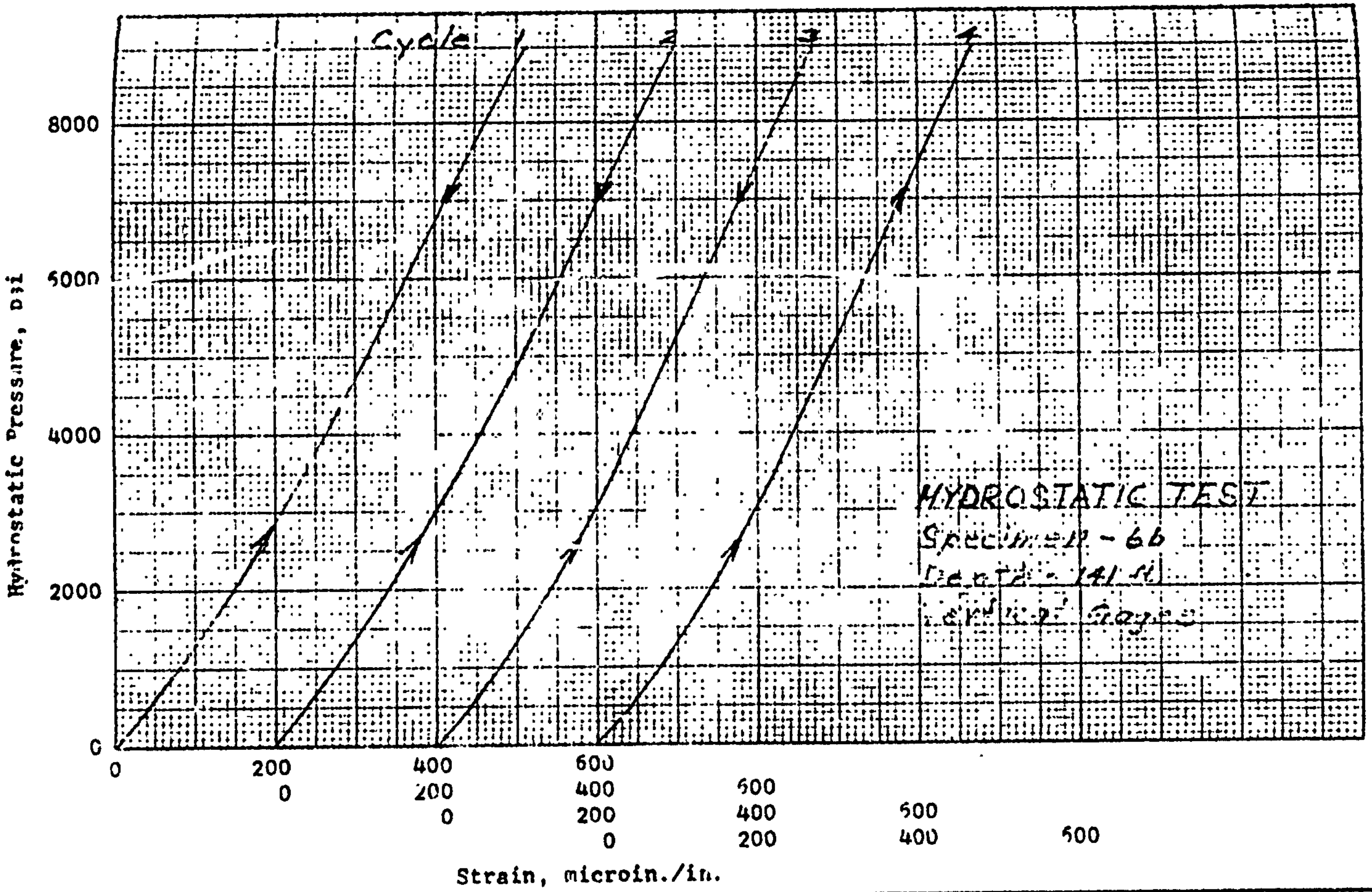

Cycle 1 2 3 4
HYDROSTATIC TEST
Specimen - 66
Hydrostatic Pressure, psi
0
2000
4000
6000
8000
0
200
400
600
Strain, microin./in.

PLATE 12

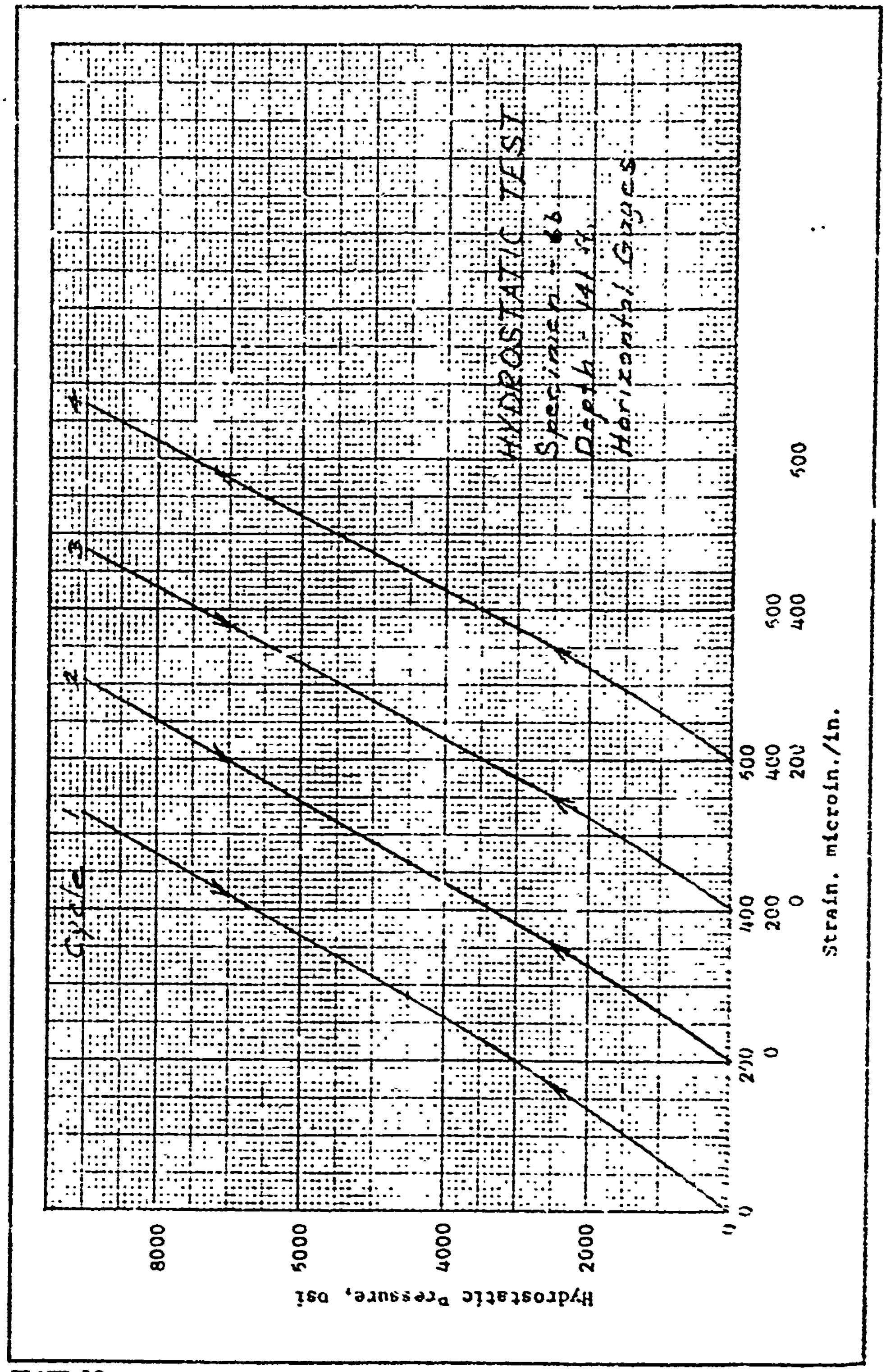

HYDROSTATIC TEST
Specimen 6b
Depth 141 ft
Horizontal Gages
Cycle
1
2
3
4
Hydrostatic Pressure, psi
Strain, microin./in.
8000
6000
4000
2000
0

PLATE 13

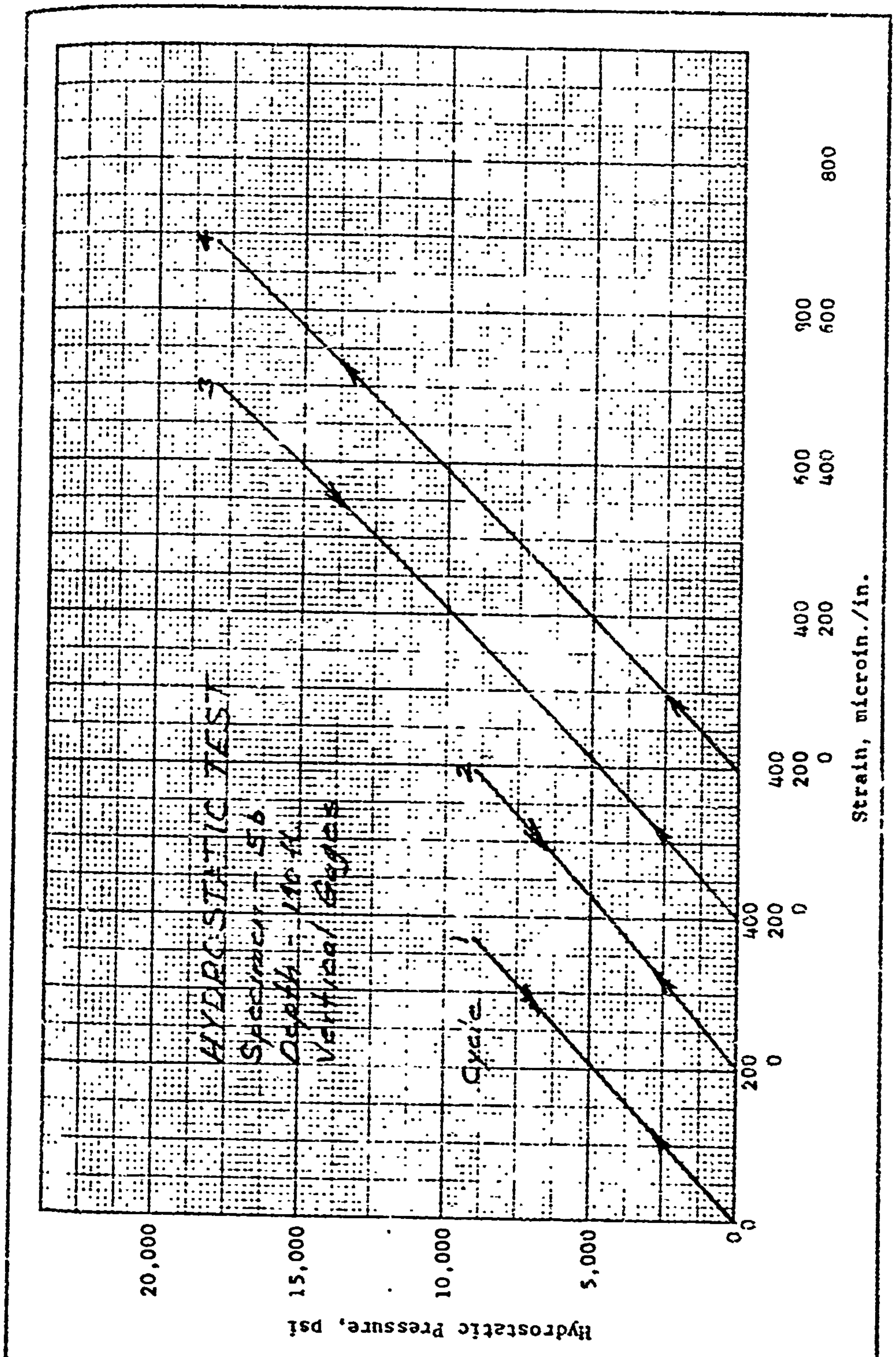

HYDROSTATIC TEST
Cycle
1
2
3
4
Hydrostatic Pressure, psi
0
5,000
10,000
15,000
20,000
Strain, microin./in.
0
200
400
600
800

PLATE 14

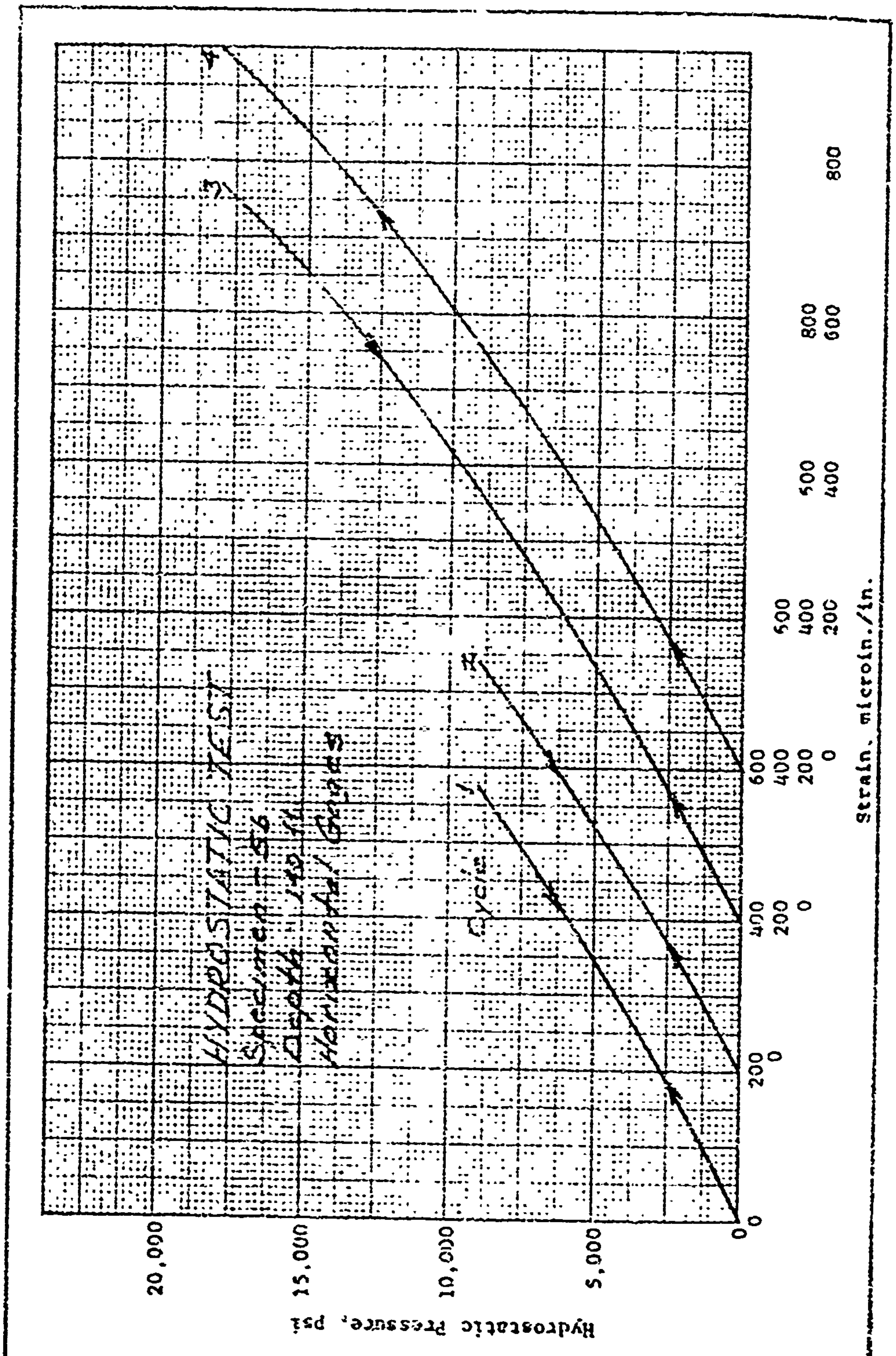

HYDROSTATIC TEST
Specimen - 56
Depth 110 ft
Horizontal Gages
Cycle
1
2
3
4
Hydrostatic Pressure, psi
20,000
15,000
10,000
5,000
0
Strain, microin./in.
0
200
0
400
200
0
600
400
200
0
600
400
200
500
400
800
600
800

PLATE 15

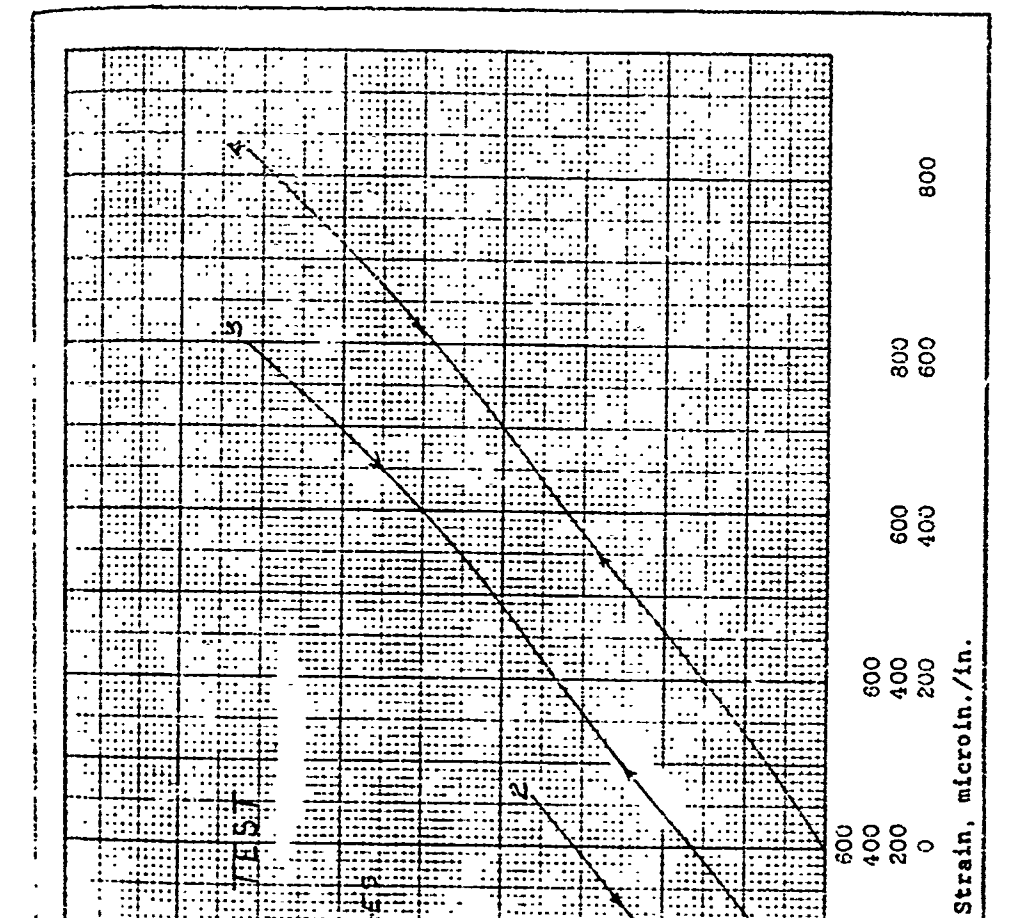
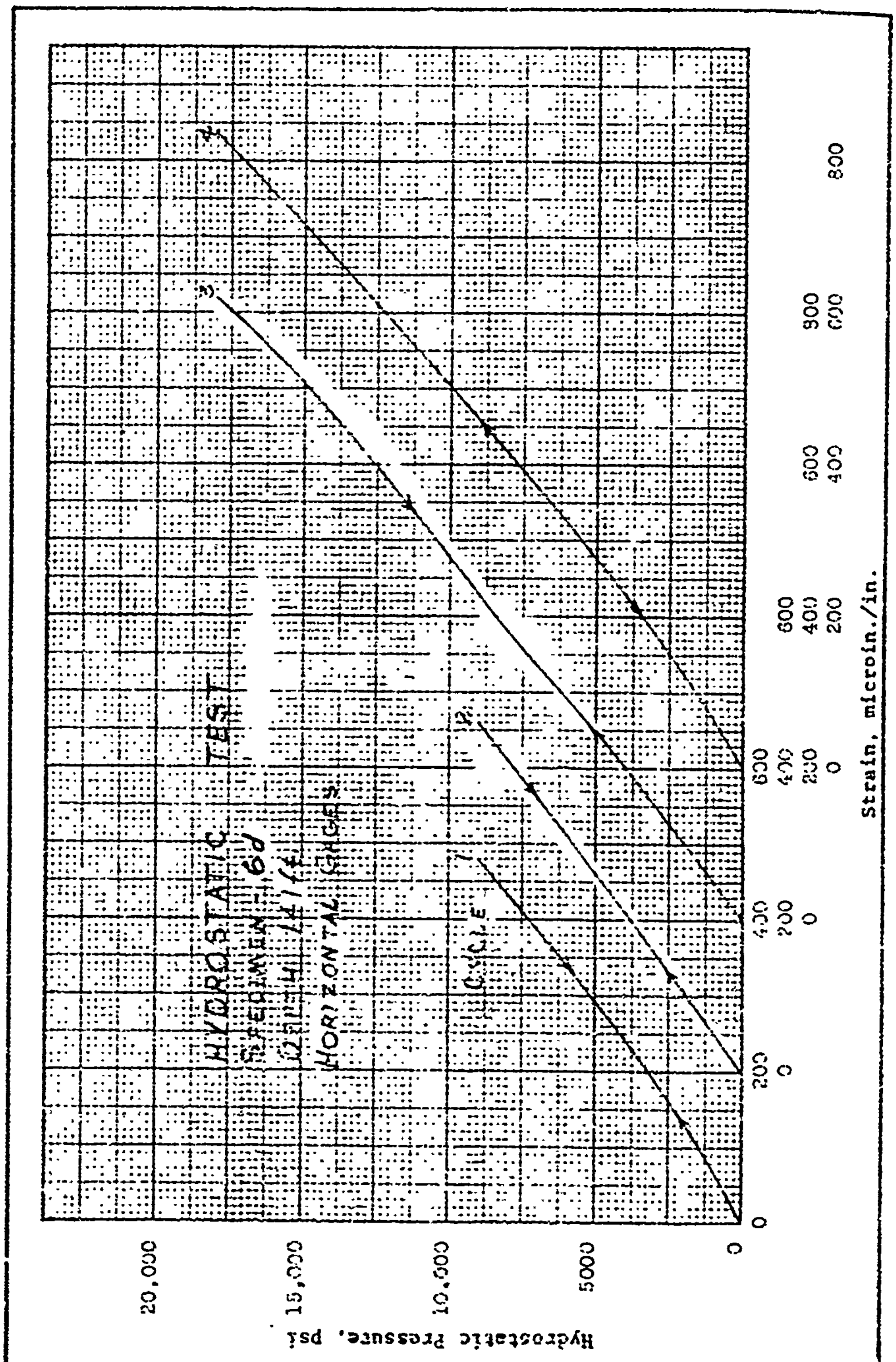

HYDROSTATIC TEST
Cycle
1
2
3
4
Hydrostatic Pressure, psi
0
5000
10,000
15,000
20,000
Strain, microin./in.
0
200
400
600
800

PLATE 16



HYDROSTATIC TEST
SPECIMEN 6d
HORIZONTAL GAGES
CYCLE
1
2
3
4
Hydrostatic Pressure, psi
0
5000
10,000
15,000
20,000
Strain, microin./in.
0
200 0
400 200 0
600 400 200 0
600 400 200
600 400
900 600
800

PLATE 17

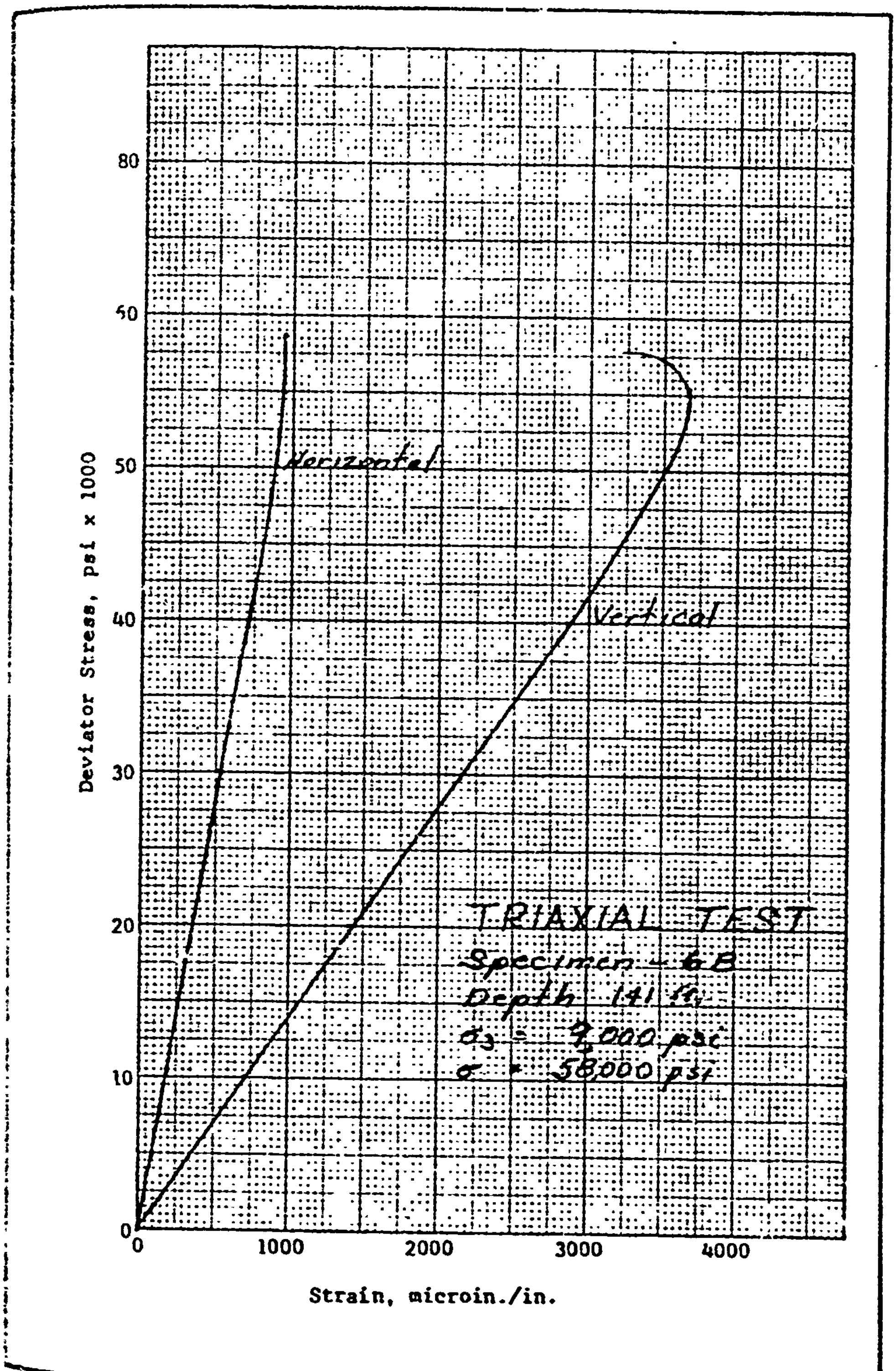
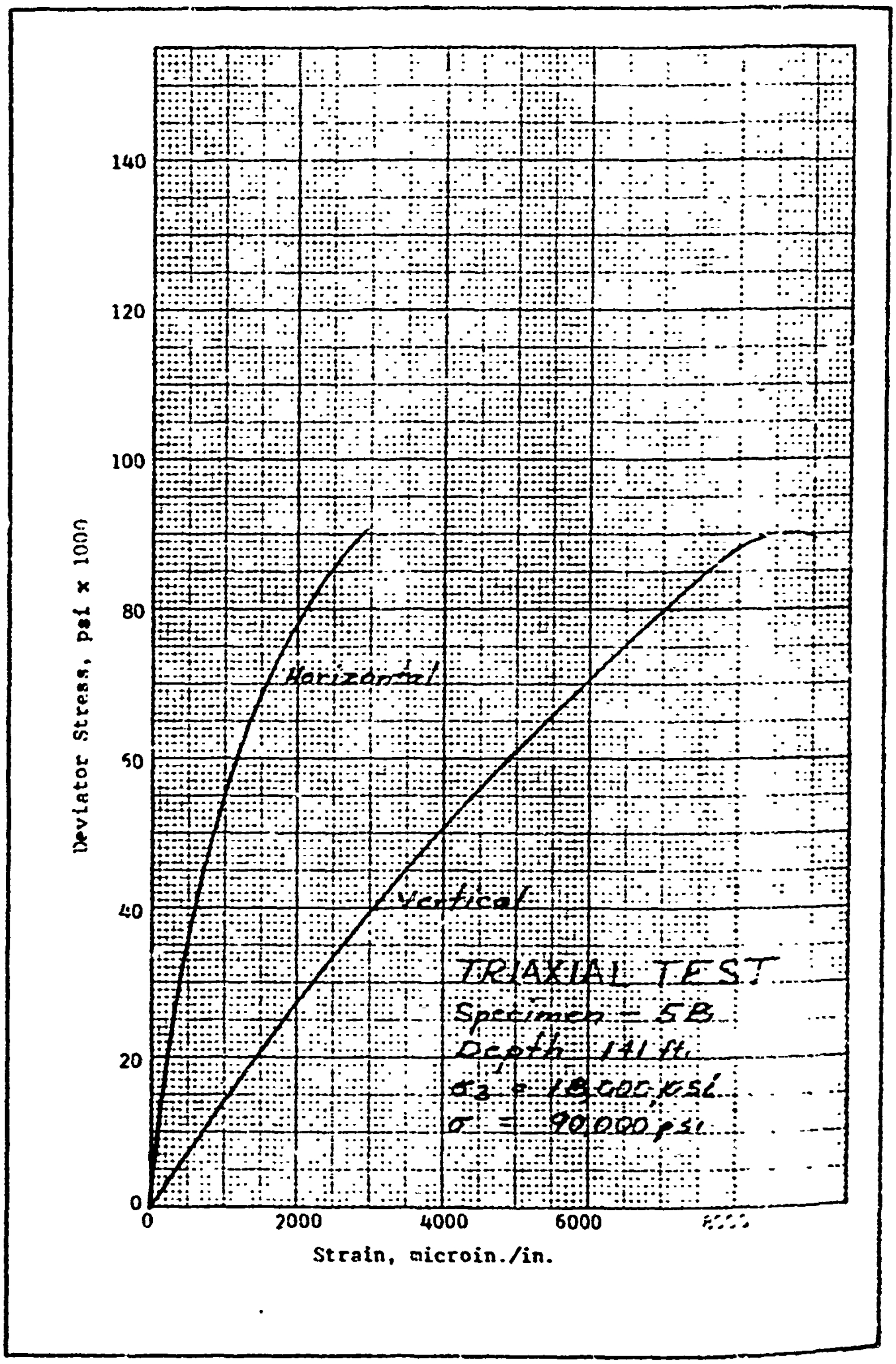
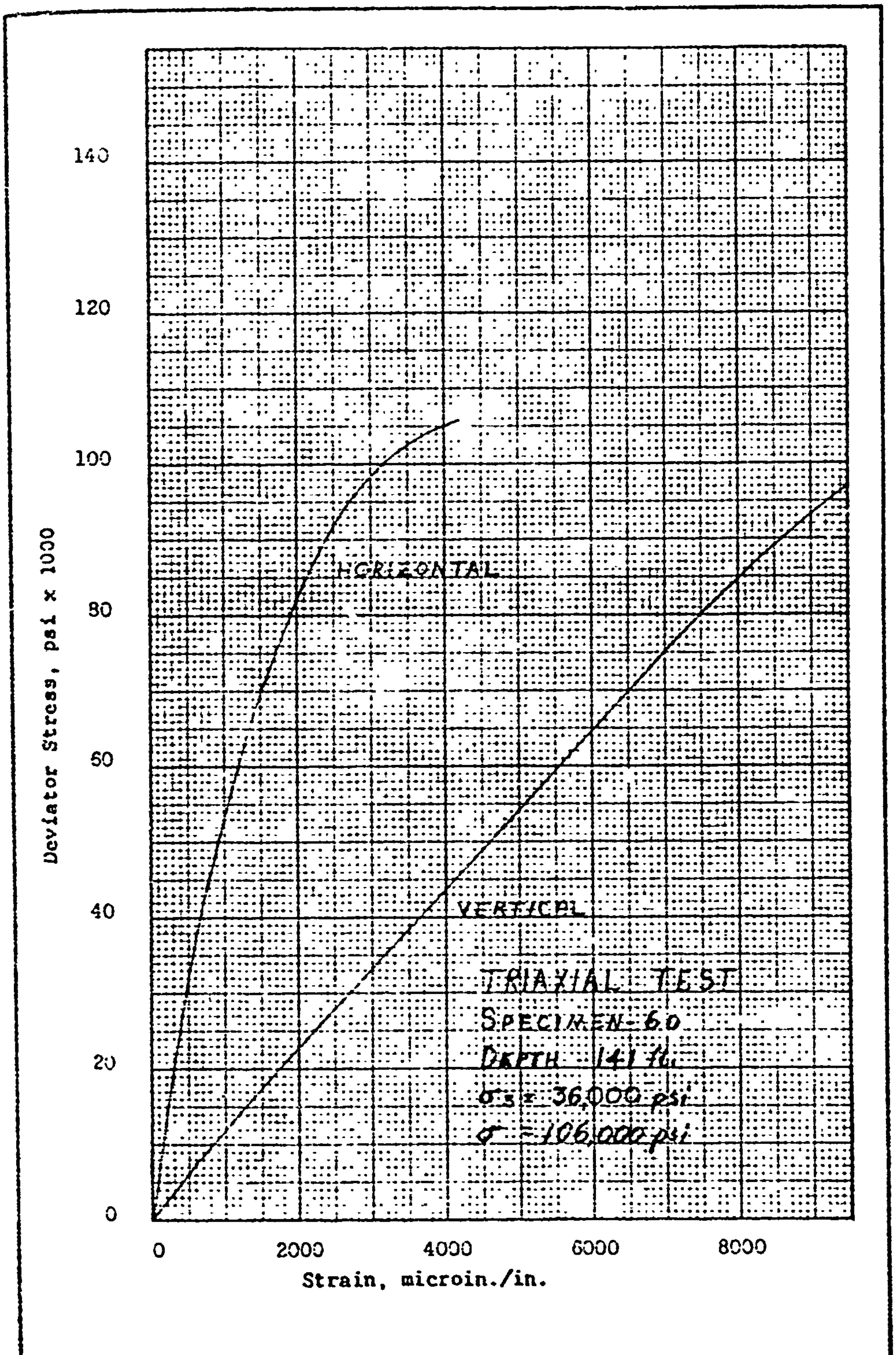

Deviator Stress, psi x 1000
80
60
50
40
30
20
10
0
Strain, microin./in.
0
1000
2000
3000
4000
Horizontal
Vertical
TRIAXIAL TEST
Specimen - 6B
Depth 141 ft.
σ3 = 2,000 psi
σ = 58,000 psi

PLATE 18



140
120
100
80
60
40
20
0
0
2000
4000
6000
Deviator Stress, psi x 1000
Strain, microin./in.
Horizontal
Vertical
TRIAXIAL TEST
Specimen — 5B
Depth 141 ft.

PLATE 19



Deviator Stress, psi x 1000
140
120
100
80
60
40
20
0
0
2000
4000
6000
8000
Strain, microin./in.
HORIZONTAL
VERTICAL
TRIAXIAL TEST
SPECIMEN 60
DEPTH 141 ft.
σ_3 = 36,000 psi
σ = 106,000 psi

PLATE 20

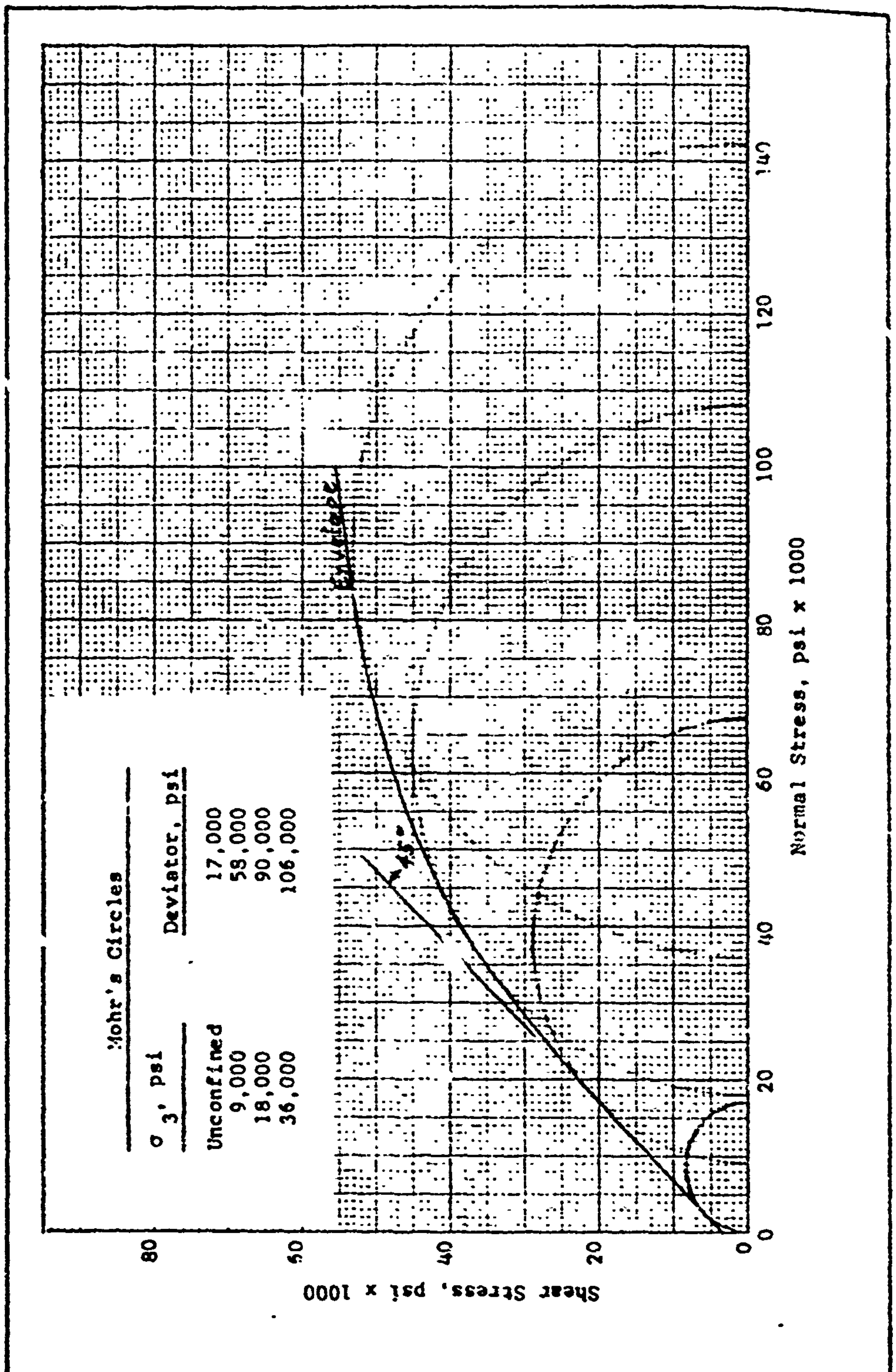
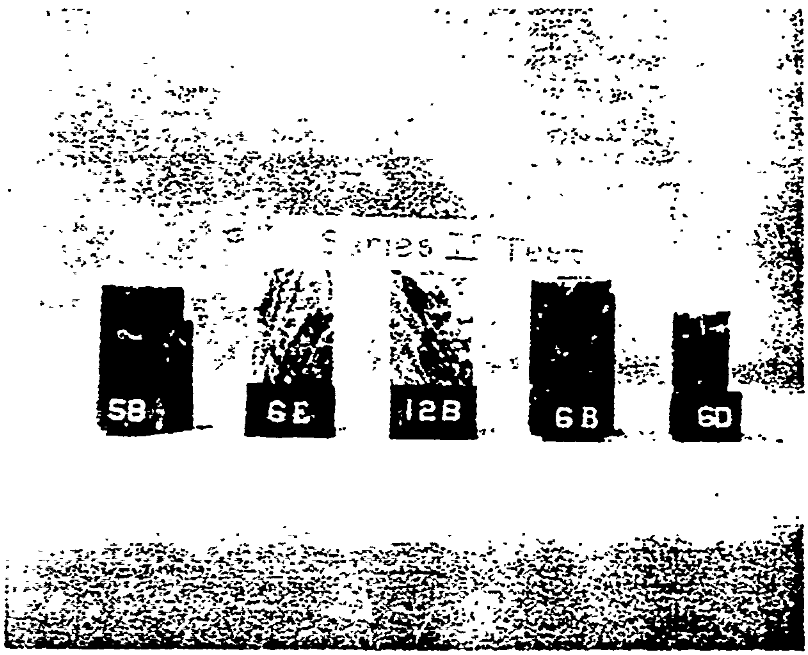
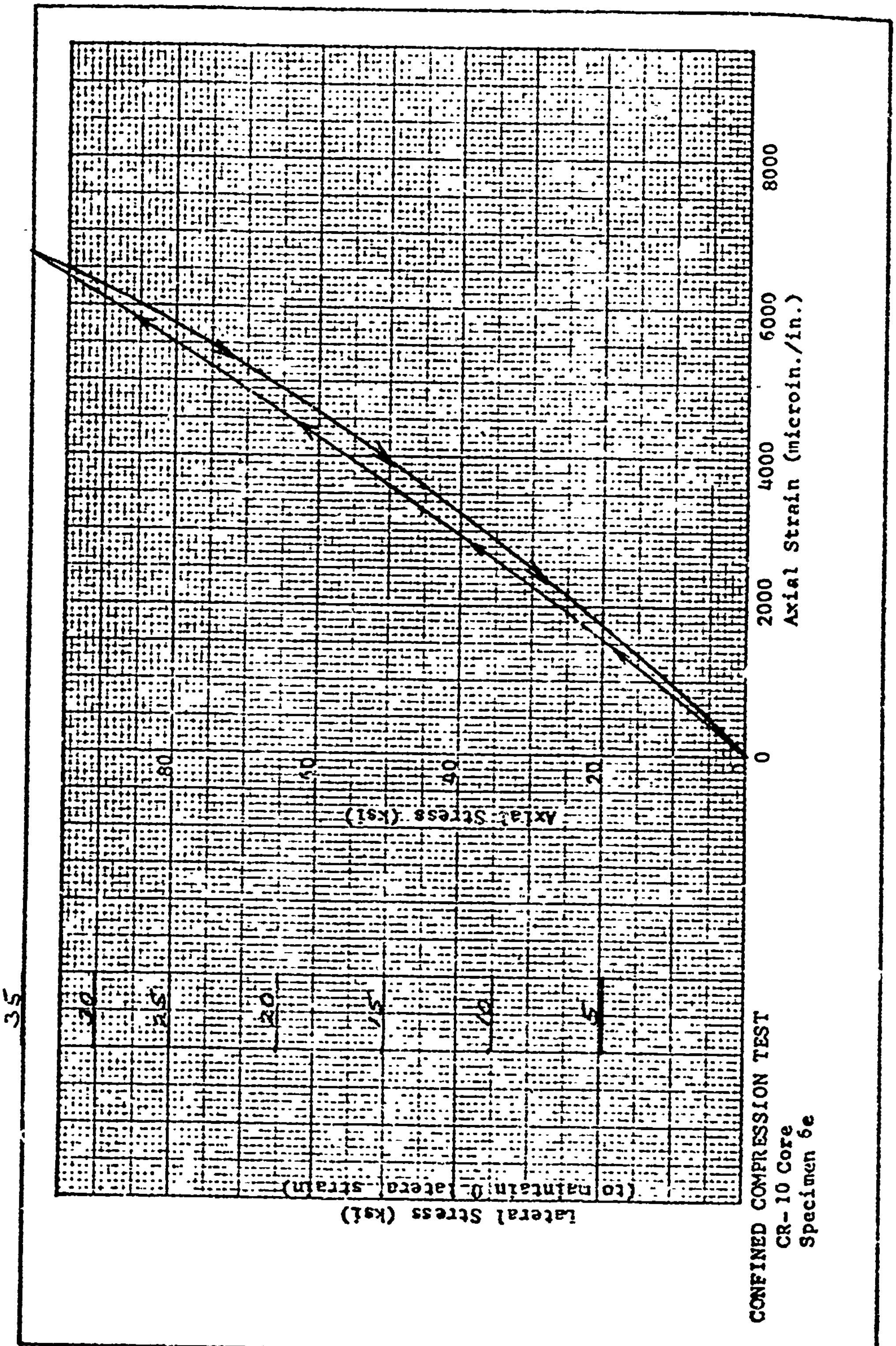

Mohr's Circles
σ3, psi
Deviator, psi
Unconfined
9,000
18,000
36,000
17,000
58,000
90,000
106,000
Envelope
45°
Normal Stress, psi x 1000
Shear Stress, psi x 1000
0
20
40
60
80
100
120
140

PLATE 21

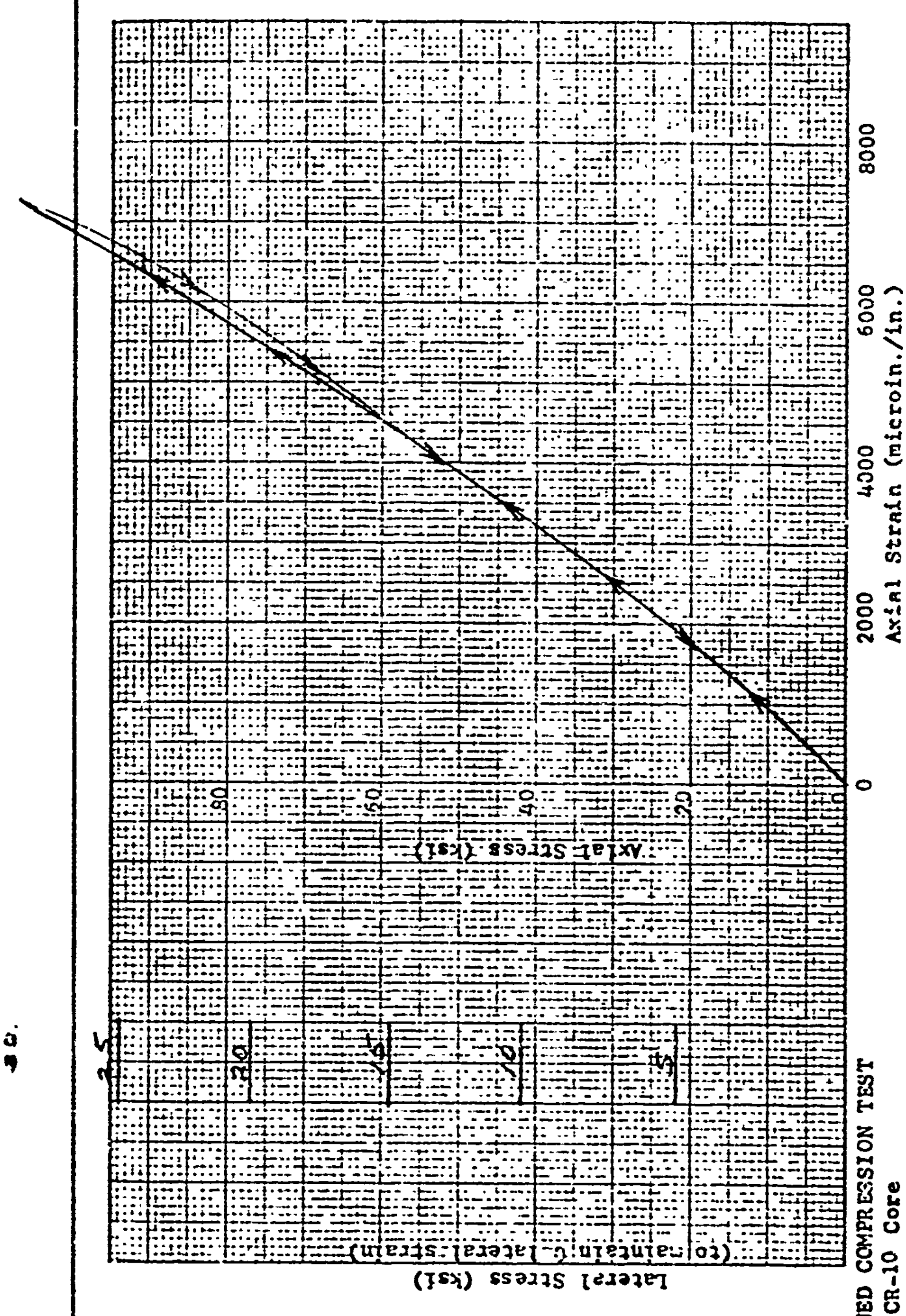


Posttest Photograph of Test Specimens



CONFINED COMPRESSION TEST
CR-10 Core
Specimen 6e
Axial Strain (microin./in.)
0
2000
4000
6000
8000
Axial Stress (ksi)
20
40
60
80
Lateral Stress (ksi)
(to maintain 0 lateral strain)
5
10
15
20
25
30
35

PLATE 23



CONFINED COMPRESSION TEST
CR-10 Core
Specimen 12b

APPENDIX K

DATA REPORT - HOLE CR-15 CORES

29 OCTOBER 1968

WARREN SITING AREA

Core No. 10 (Hole CR-15)

1. Nineteen pieces of core were received from the Warren area on 11 October 1968, designated CR-15 core. Numbers were assigned as indicated.

Sample	Specimen Designation	Approximate Depth, ft
A	1	75
A	2	76
A	3	78
A	4	80
A	5	93
A	6	94
A	7	95
B	8	109
B	9	110
B	10	111
C	11	119
C	12	120
C	13	120
C	14	121
C	15	188
C	16	189
C	17	190
C	18	191
C	19	192

2. The hole from which the core was taken was located in Albany County, Wyoming, township 21N, range 72W, section 8.

Warren Siting Area: Core No. 10 (Hole CR-15); Series I Tests

Results

Petrographic examination

3. About 13 ft of NX core from several depths in hole CR-15 was received in October 1968 for testing. The petrographic specimens are identified below:

CD Serial No.	Piece No.	Depth, ft	Length, ft
SAMSO-2 DC-8	2	76	1/4
SAMSO-2 DC-8	9 (top portion)	110	1/3
SAMSO-2 DC-8	17 (top portion)	190	1/3

4. The core sample included banded pegmatitic gneiss as well as medium-grained amphibolite. The distribution in the core samples is shown below:

Piece No.	Approximate Length, ft	Rock Type
1-7	4)	Medium-grained amphibolite
11-13	2)	
8-10	2	White gneissic pegmatite
14-19	5-1/2	Banded amphibolite and pegmatite

5. The entire core is metamorphic rock. Most of the fracture surfaces appeared to be fresh, but a few were old breaks, partially covered with a thin layer of calcite.

6. The test procedure was generally similar to that followed for the other samples in this test series. X-ray diffraction patterns of the dark amphibolite and of the pale gray pegmatitic gneiss were made. The banded rock was examined on sawed and broken surfaces. Two thin sections of amphibolite were examined.

7. The typical rock of this core is medium-grained amphibolite composed largely of hornblende and plagioclase, with some quartz and ·le chlorite, biotite, yellow iron sulfide, and probably pyroxene.

8. The white gneissic pegmatite in pieces 8-10 is coarser grained than the amphibolite and consists largely of plagioclase and quartz with a little biotite.

9. The material in pieces 14-19 is predominantly amphibolite with many narrow bands of white gneissic pegmatite.

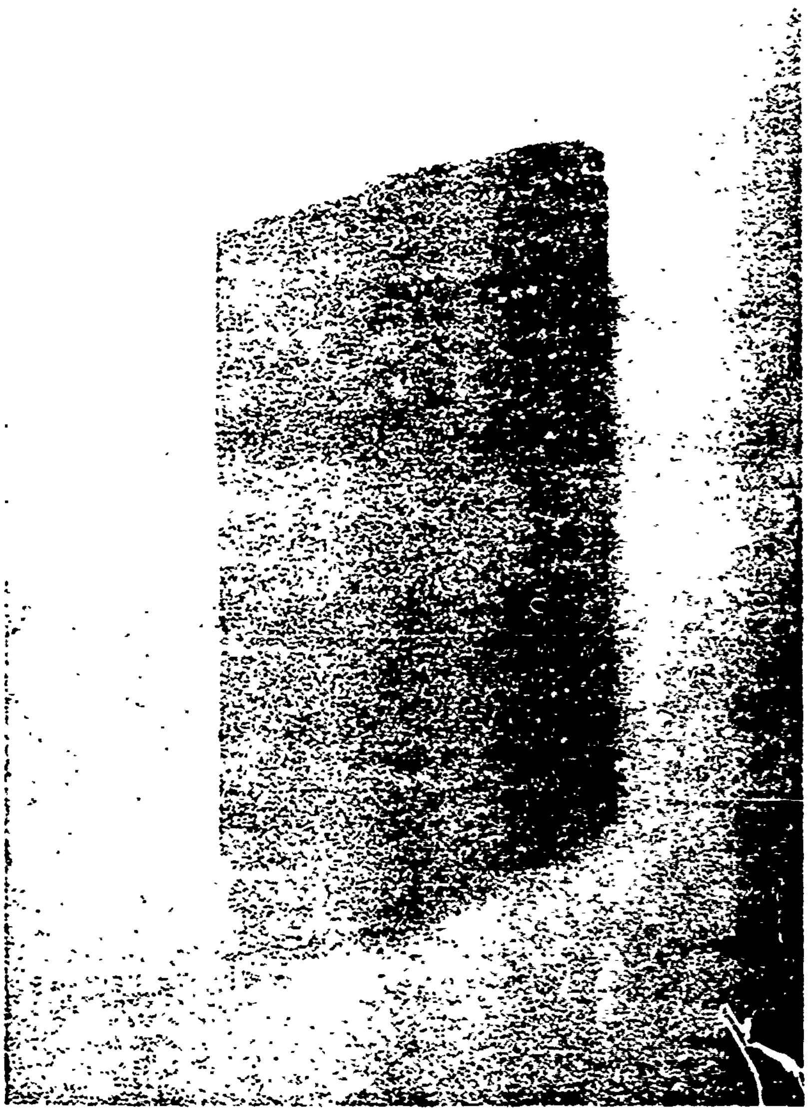
10. Photograph 1 shows the well-developed foliation and the grain size of the amphibolite. Photograph 2 illustrates the appearance of the banded amphibolite gneiss.

Schmidt number, specific gravity, porosity, tensile strength

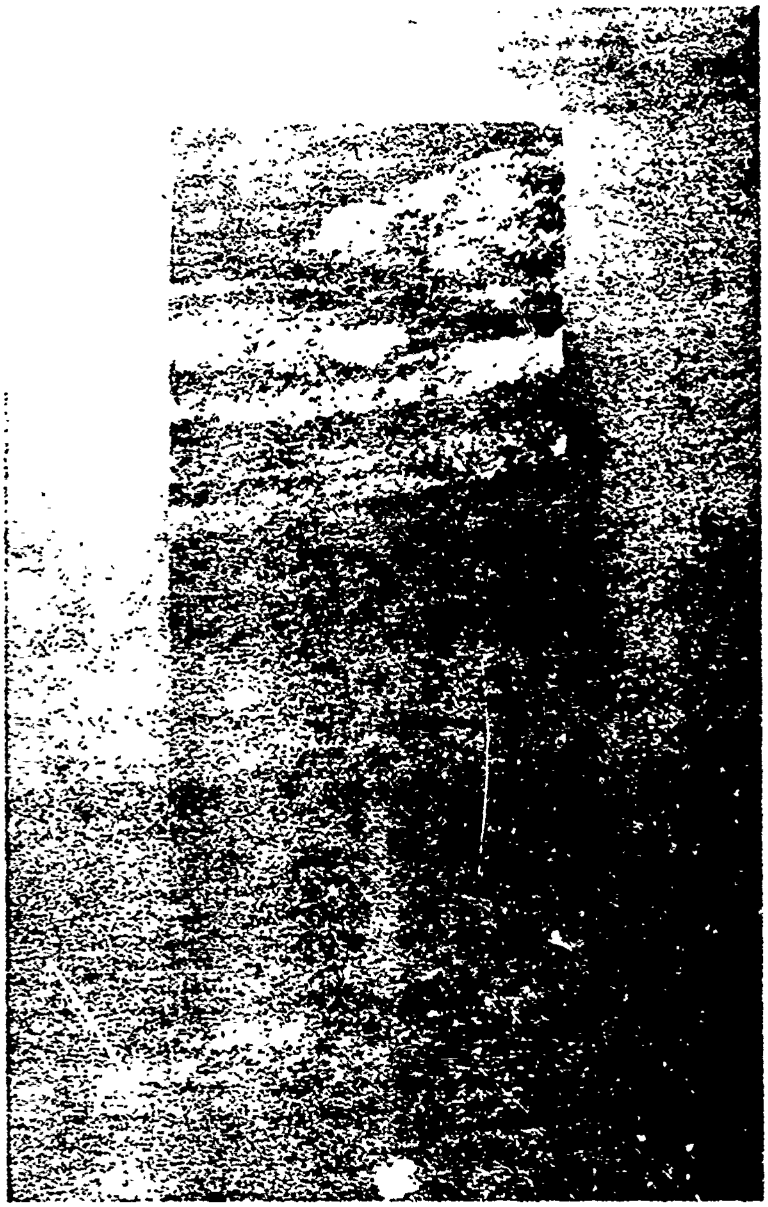
11. Three specimens from each depth interval were selected for the basic tests. Results are given below:

Core	Schmidt Rebound Number	Schmidt Standard Deviation	Specific Gravity	% Porosity	Tensile Strength, psi
		Sample A - 50-ft Depth			
2a	50.7	2.63	3.053	0.0	2260
3b	52.7	3.70	3.078	0.0	2150
7b	54.2	4.17	3.062	0.0	2375
Avg	52.5	3.50	3.064	0.0	2260
		Sample B - 110-ft Depth			
8a	57.0	3.20	2.674	0.0	1070
8c	55.7	5.03	2.704	0.0	1240
10b	59.9	4.02	2.691	0.0	1095
Avg	57.5	4.08	2.690	0.0	1135
		Sample C - 190-ft Depth			
14b	53.2	3.47	2.898	0.0	1795
16b	54.8	4.61	2.965	0.0	2575
18a	53.7	4.42	2.931	0.0	2300
Avg	53.9	4.17	2.931	0.0	2220

12. The light-colored gneiss from the 110-ft depth is substantially different from the darker material. The banded rock from the 110-ft depth apparently represents an average combination of the two extremes. The unusually high indicated tensile strengths from the upper and lower depths should be considered with respect to the nature of the rock. Tested across the bands, as done here, foliated specimens would be expected to give a higher indicated strength than specimens tested along the foliation.



Photograph 1. Sawed surface of piece 2 from core hole CR-15, depth 75 ft, natural size.



Photograph 2. Banded amphibolite gneiss, natural size, from piece 17a.

Warren Siting Area: Core No. 10 (Hole CR-15); Series I Tests

Shear tests

13. Direct single plane shear tests were conducted on samples of the foliated rock. Shear strengths of 1140, 1225, and 1285 psi (average 1215 psi) were obtained on specimens 13a, 16a, and 18b, respectively. The shear strengths are unusually low when compared to the tensile and compressive strengths. However, they are probably representative of the shear strength of the material since the shearing force was applied almost parallel to the foliation. A posttest photograph of the test specimens is given in plate 1.

Unconfined compressive strength tests

14. Unconfined compressive strength tests were conducted on three specimens each from the three depth intervals. One of each group was a cyclic test. Results are given below:

Core No.	Depth, ft	Unconfined Compressive Strength, psi
3a	78	27,500
5a*	93	27,700
7a	95	37,100
Avg	89	30,770
8b*	109	27,200
9b	110	23,200
10a	111	37,200
Avg	110	29,200
13b*	120	40,700
16c	189	30,900
17b	190	27,100
Avg	166	32,900

* Cycled.

15. The difference in material is not perceptible in the compressive strength results; however, the strength is quite variable which could be attributed to the foliated nature of the rock. All specimens had two vertical and two horizontal electrical gages affixed in order to monitor strain during loading. Unloading cycles were made at 5000-psi intervals up to 15,000 psi on the cyclic specimens. Stress-strain curves are given in plates 2-10. The hysteresis loops were small and closed. A posttest photograph of the test specimens, plate 11, shows the nature of failure, steep sided coning.

Warren Siting Area: Core No. 10 (Hole CR-15); Series I Tests

Moduli of deformation

16. Young's modulus, shear modulus, bulk modulus, and Poisson's ratio were computed on three samples by the dynamic (fundamental frequency) method and on the unconfined compressive strength specimens statically at approximately 50 percent of the ultimate strength. Results are given below:

Core No.	Young's Modulus of Elasticity, psi x 10^6	Shear Modulus (Modulus of Rigidity), psi x 10^6	Bulk Modulus, psi x 10^6	Poisson's Ratio
		Dynamically		
6	15.22	6.50	7.69	0.17
8	*	*	*	*
16	13.52	5.80	6.83	0.17
		Statically		
3a	13.10	5.24	8.73	0.25
5a	15.20	5.98	11.01	0.27
7a	16.00	6.35	11.11	0.26
8b	11.20	4.66	6.22	0.23
9b	11.60	4.79	6.66	0.21
10a	12.00	4.88	7.41	0.23
13b	15.30	5.57	10.45	0.24
16c	13.30	5.32	8.87	0.25
17b	13.50	5.53	8.04	0.22

* Could not be determined.

17. A cursory examination of the data reveals that the rock from the middle interval, specimens 8b, 9b, and 10a, is slightly more deformable than the other material.

Velocity measurements

18. The compressional wave velocity was determined directly as the sonic propagation velocity, and the shear wave velocity was determined from the torsional frequency obtained in the moduli determinations.

Warren Siting Area: Core No. 10 (Hole CR-15); Series I Tests

Core No.	Compressional Velocity, fps	Shear Velocity, fps
6	18,975	12,705
8	15,905	*
15	18,280	12,130

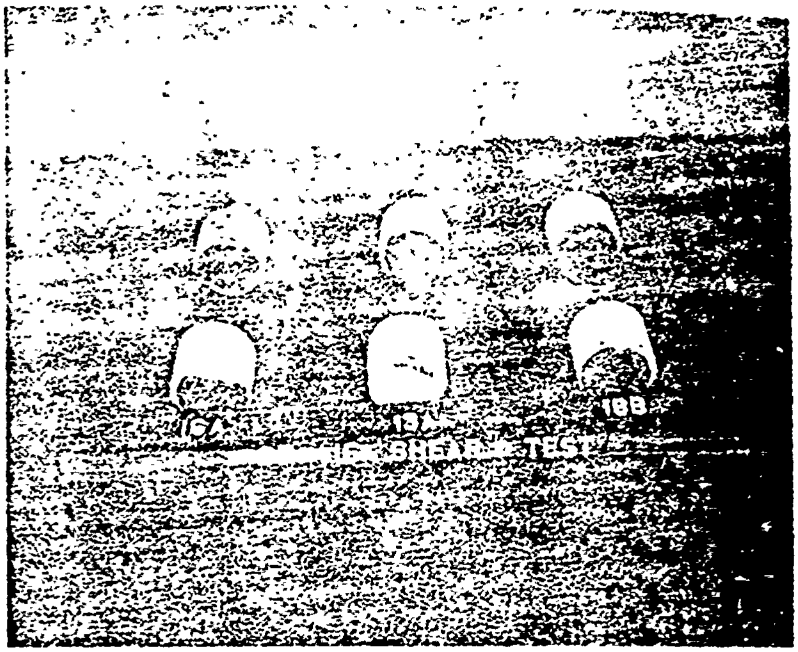
*Could not be determined.

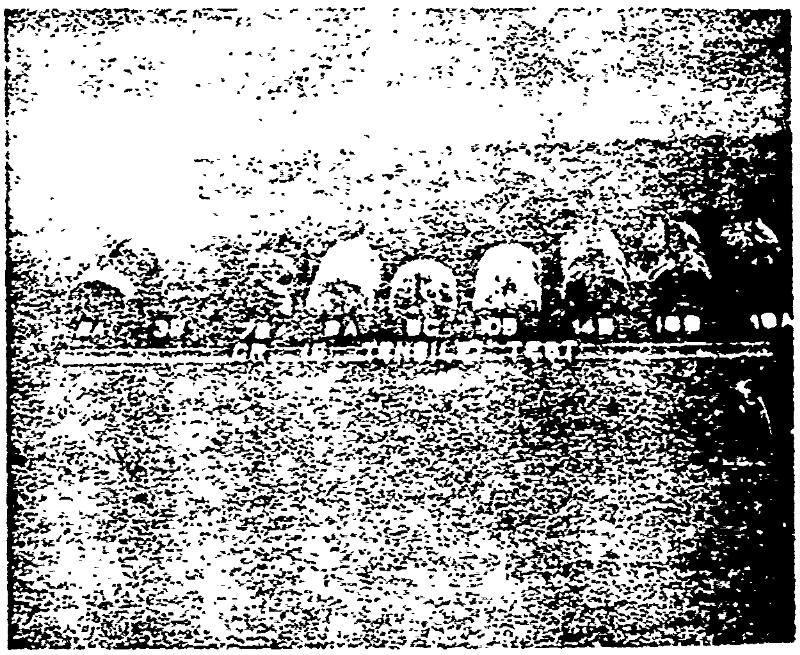
The shear velocity is approximately 67 percent of the compressional velocity.

Conclusions

19. The CR-15 core is identified as an amphibolite. The three samples received from three depth intervals were different in physical properties as indicated below:

Property	Upper	Middle	Lower
Color	Dark	Light	Banded
Specific gravity	3.06	2.69	2.93
Percent porosity	0.0	0.0	0.0
Compressive strength, psi	30,770	29,200	32,900
Tensile strength, psi	2,260	1,135	2,220
Young's modulus, psi x 10^6	14.8	11.5	14.4
Compressional wave velocity, fps	18,975	15,905	18,280





Posttest Photographs

PLATE 1

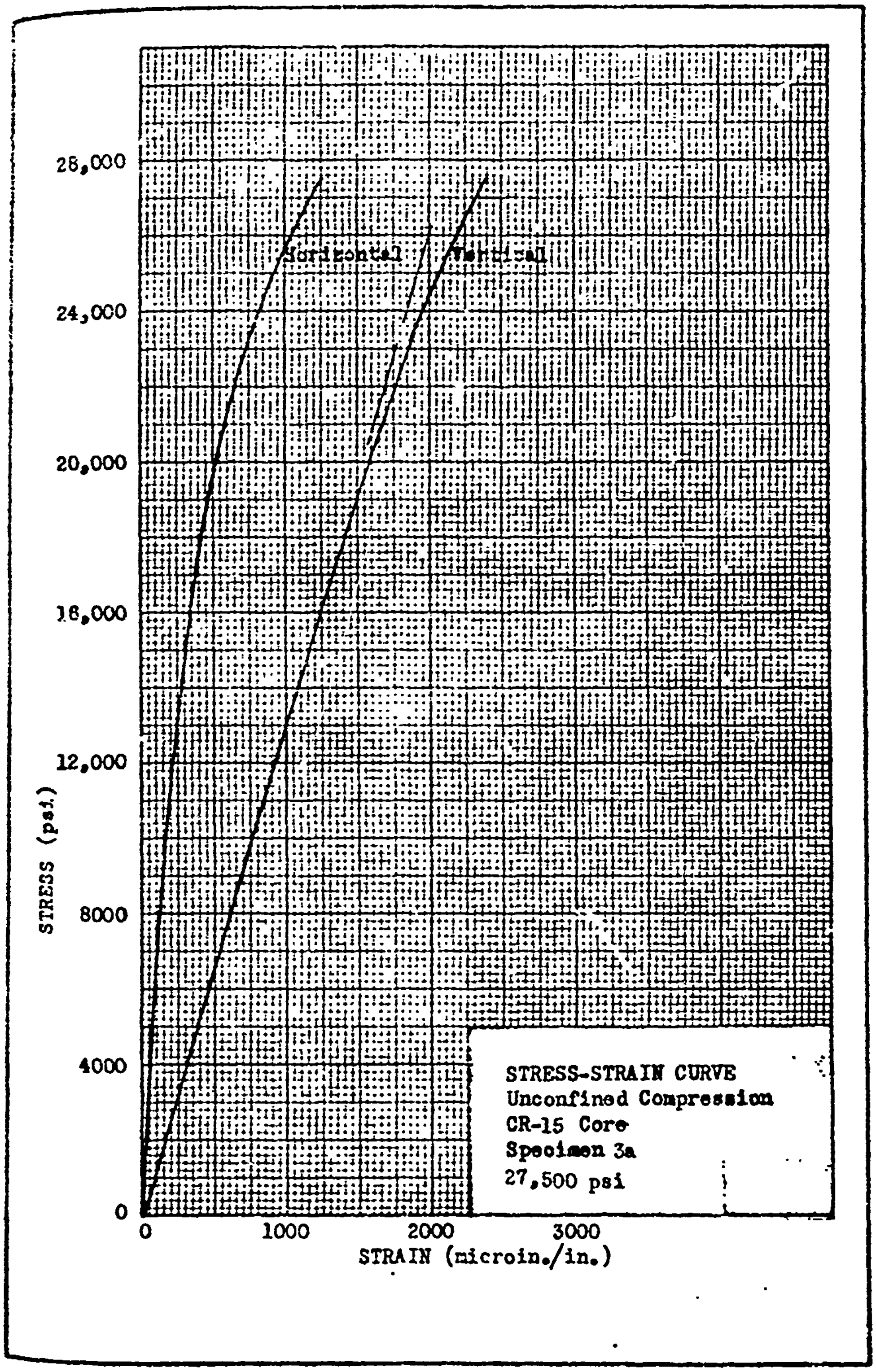

28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
STRAIN (microin./in.)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR-15 Core
Specimen 3a
27,500 psi

PLATE 2

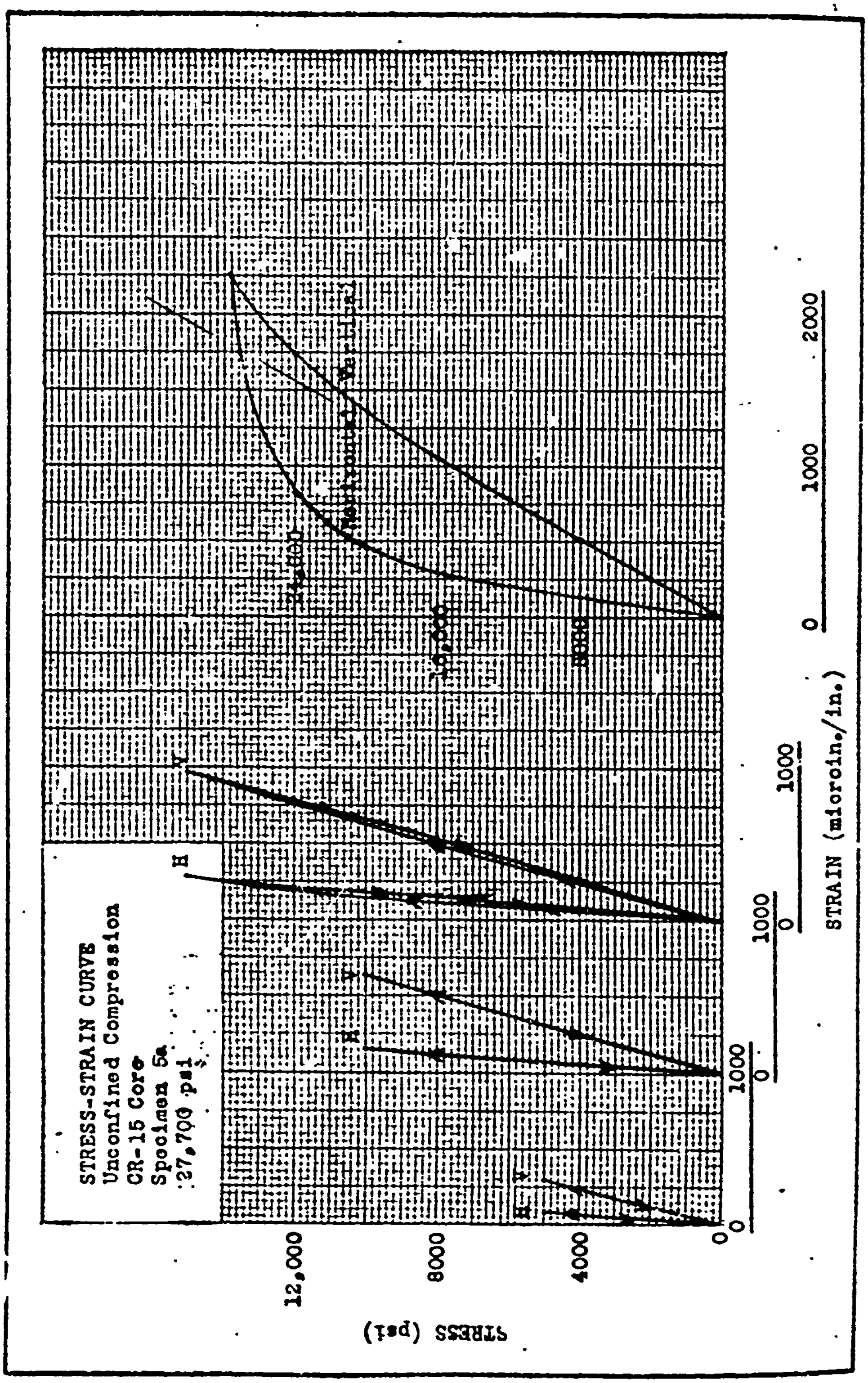
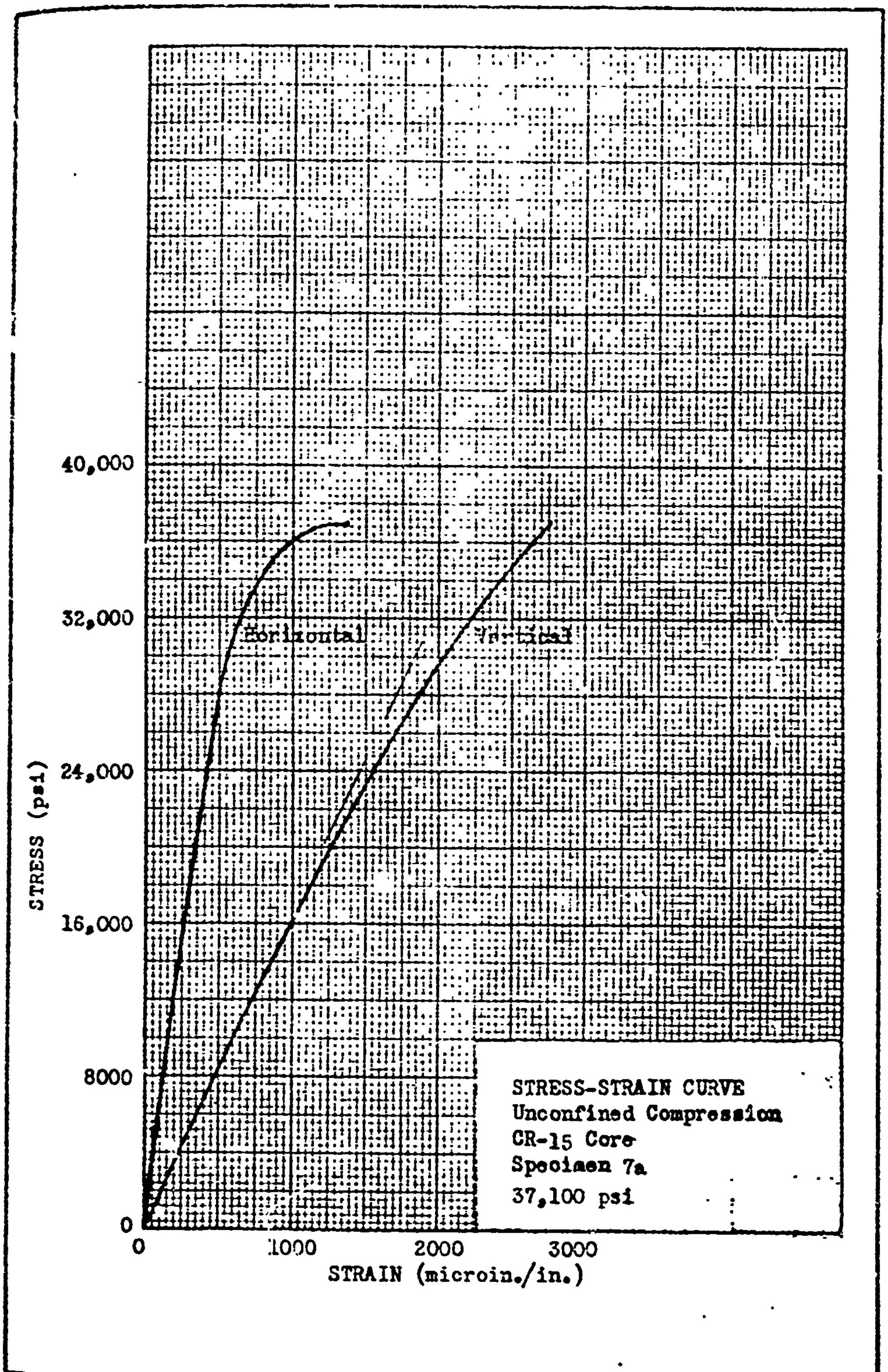

STRESS-STRAIN CURVE
Unconfined Compression
CR-15 Core
Specimen 5a
27,700 psi
STRESS (psi)
12,000
8000
4000
0
STRAIN (microin./in.)
0
1000
2000
H
V

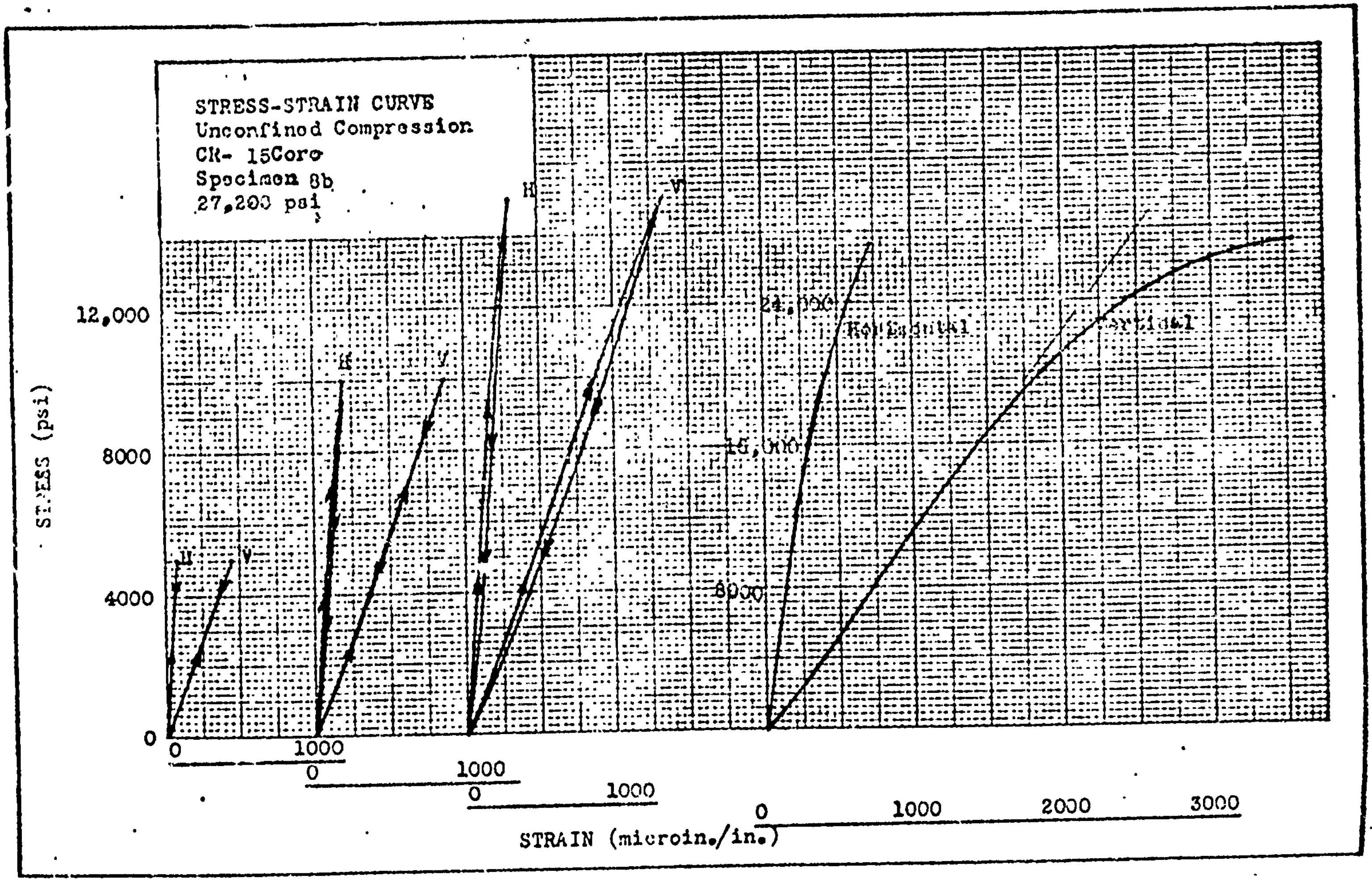
PLATE 3

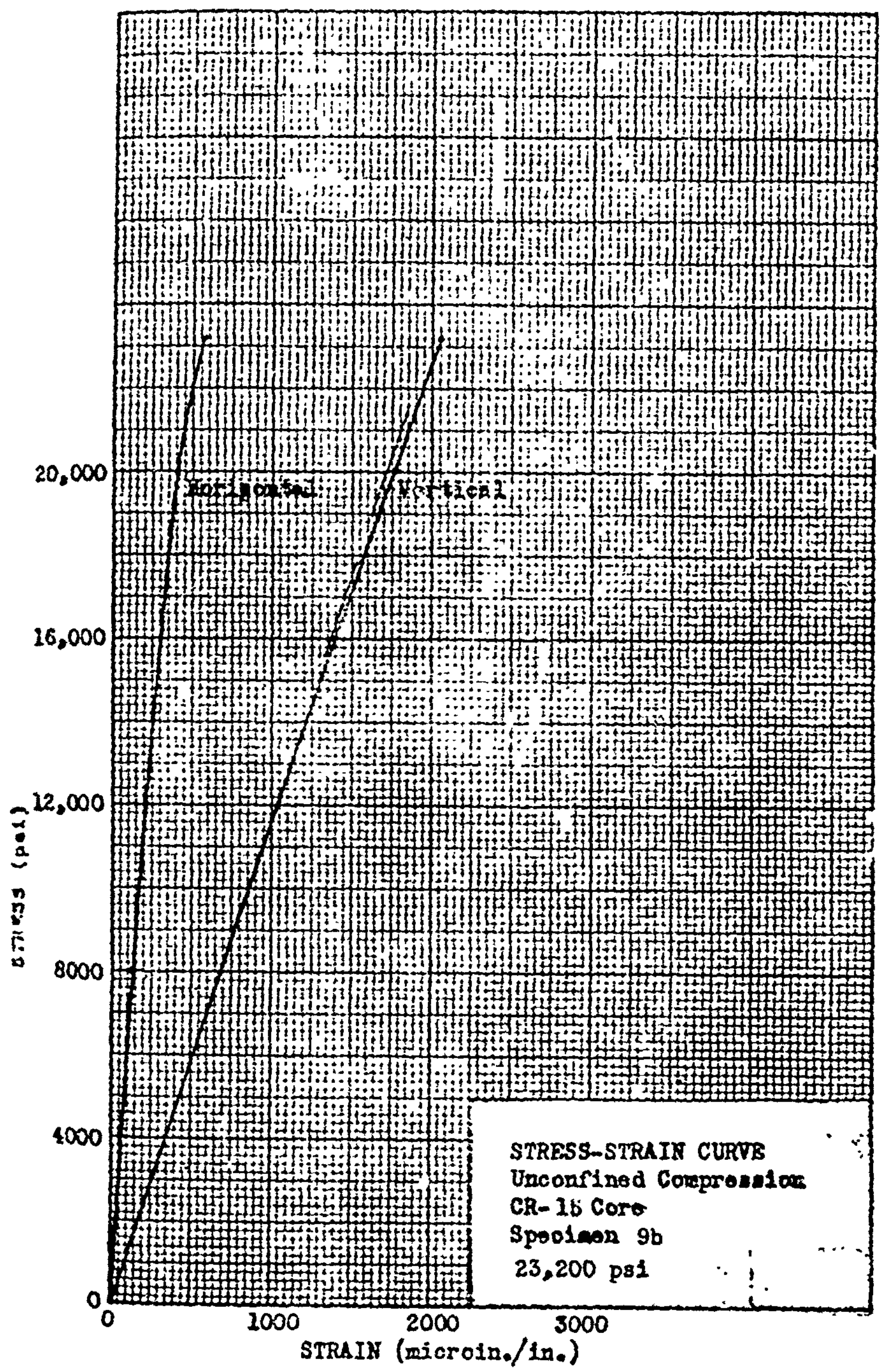


40,000
32,000
24,000
16,000
8000
0
STRESS (psi)
Horizontal
Vertical
0
1000
2000
3000
STRAIN (microin./in.)
STRESS-STRAIN CURVE
Unconfined Compression
CR-15 Core
Specimen 7a
37,100 psi

PLATE 4

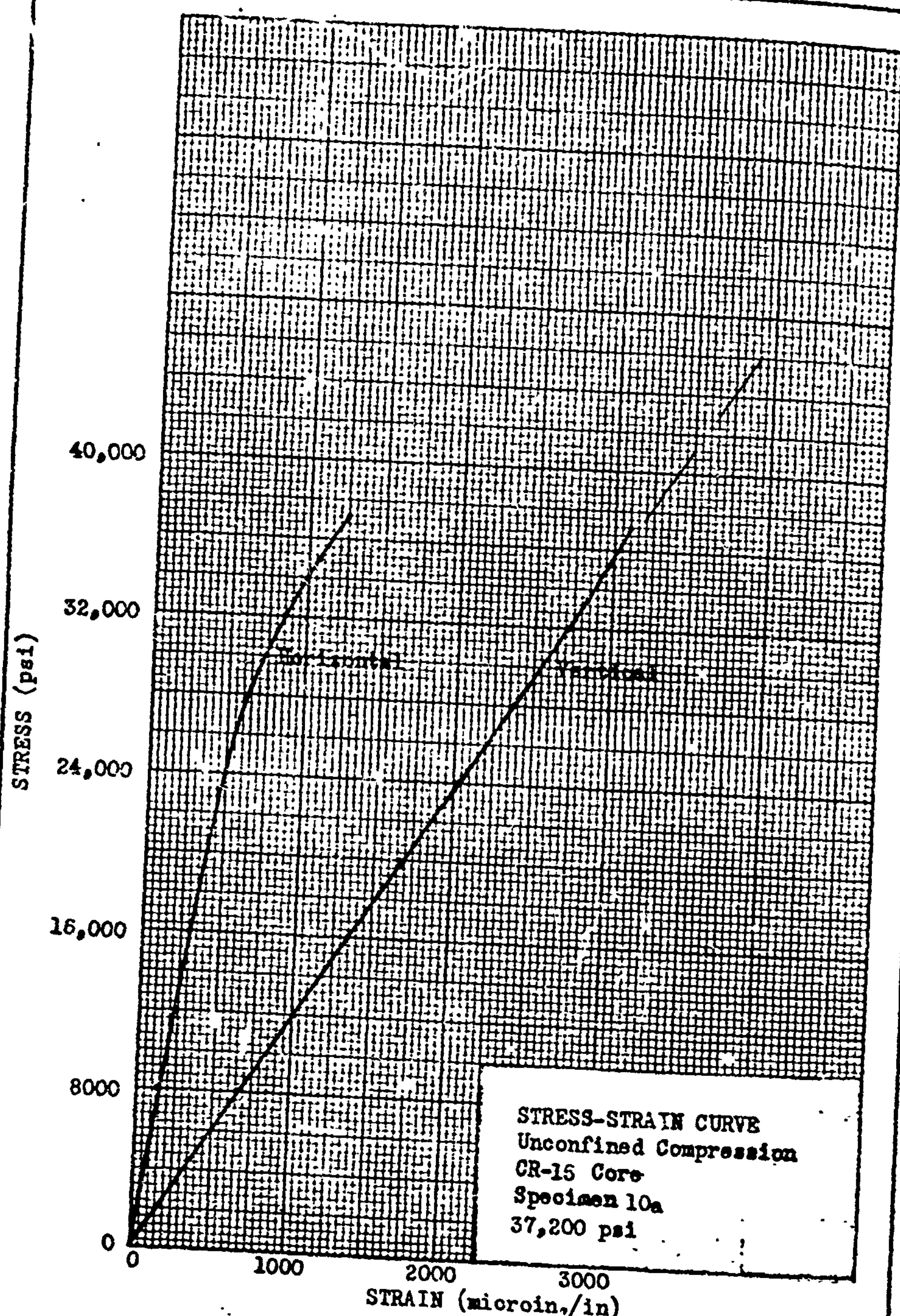
PLATE 5


STRESS-STRAIN CURVE
Unconfined Compression
CR- 15Core
Specimen 8b
27,200 psi
STRESS (psi)
12,000
8000
4000
0
H
V
1000
STRAIN (microin./in.)
3000
2000
24,000
16,000
8000
Horizontal
Vertical



20,000
16,000
12,000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
STRAIN (microin./in.)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR-1b Core
Specimen 9b
23,200 psi

PLATE 6



STRESS (psi)
40,000
32,000
24,000
16,000
8000
0
0
1000
2000
3000
STRAIN (microin./in)
Horizontal
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR-15 Core
Specimen 10a
37,200 psi

PLATE 7

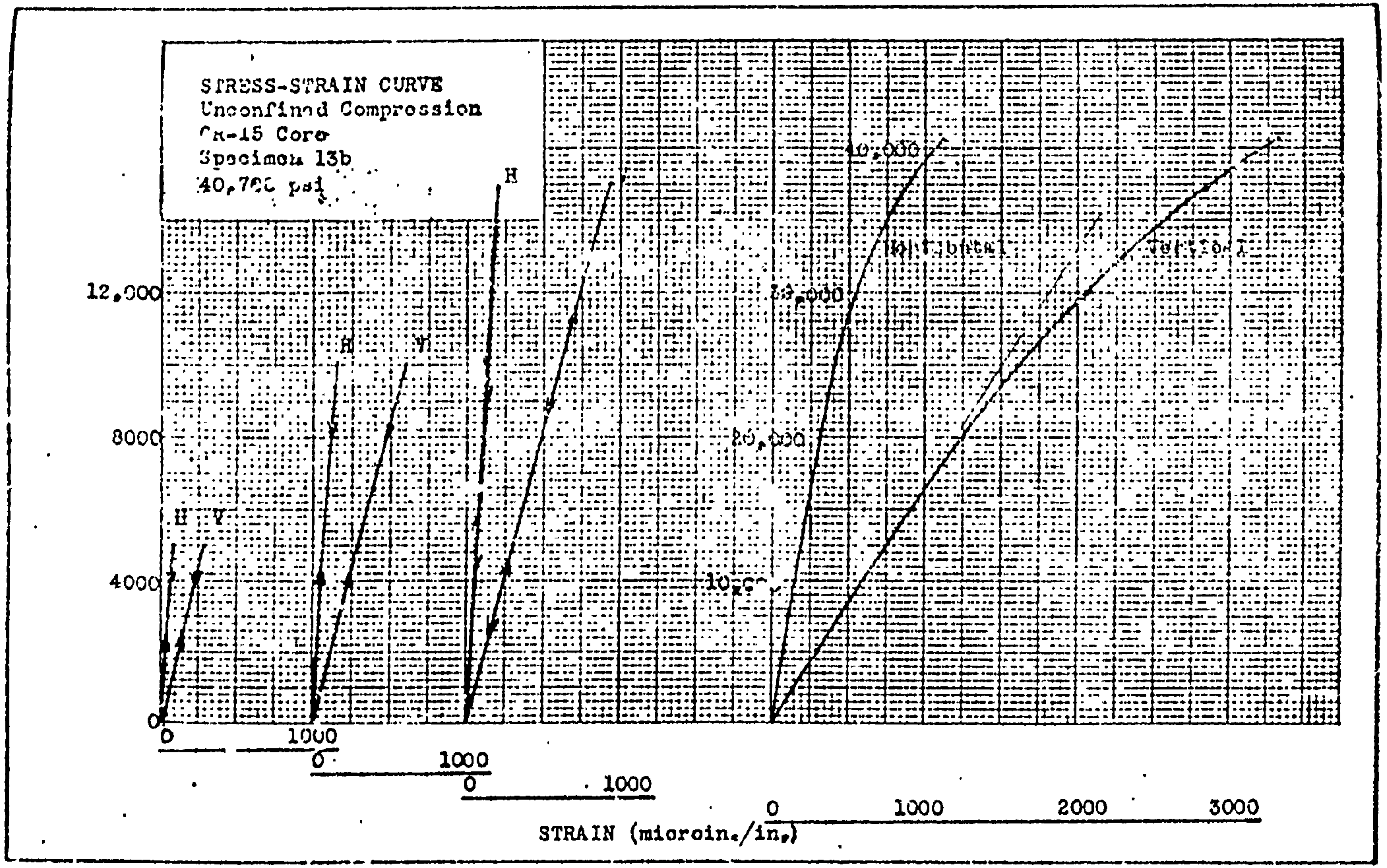

STRESS-STRAIN CURVE
Unconfined Compression
CK-15 Core
Specimen 13b
40,700 psi
12,000
8000
4000
0
H
V
1000
Horizontal
Vertical
40,000
30,000
20,000
10,000
2000
3000
STRAIN (microin./in.)

PLATE 8

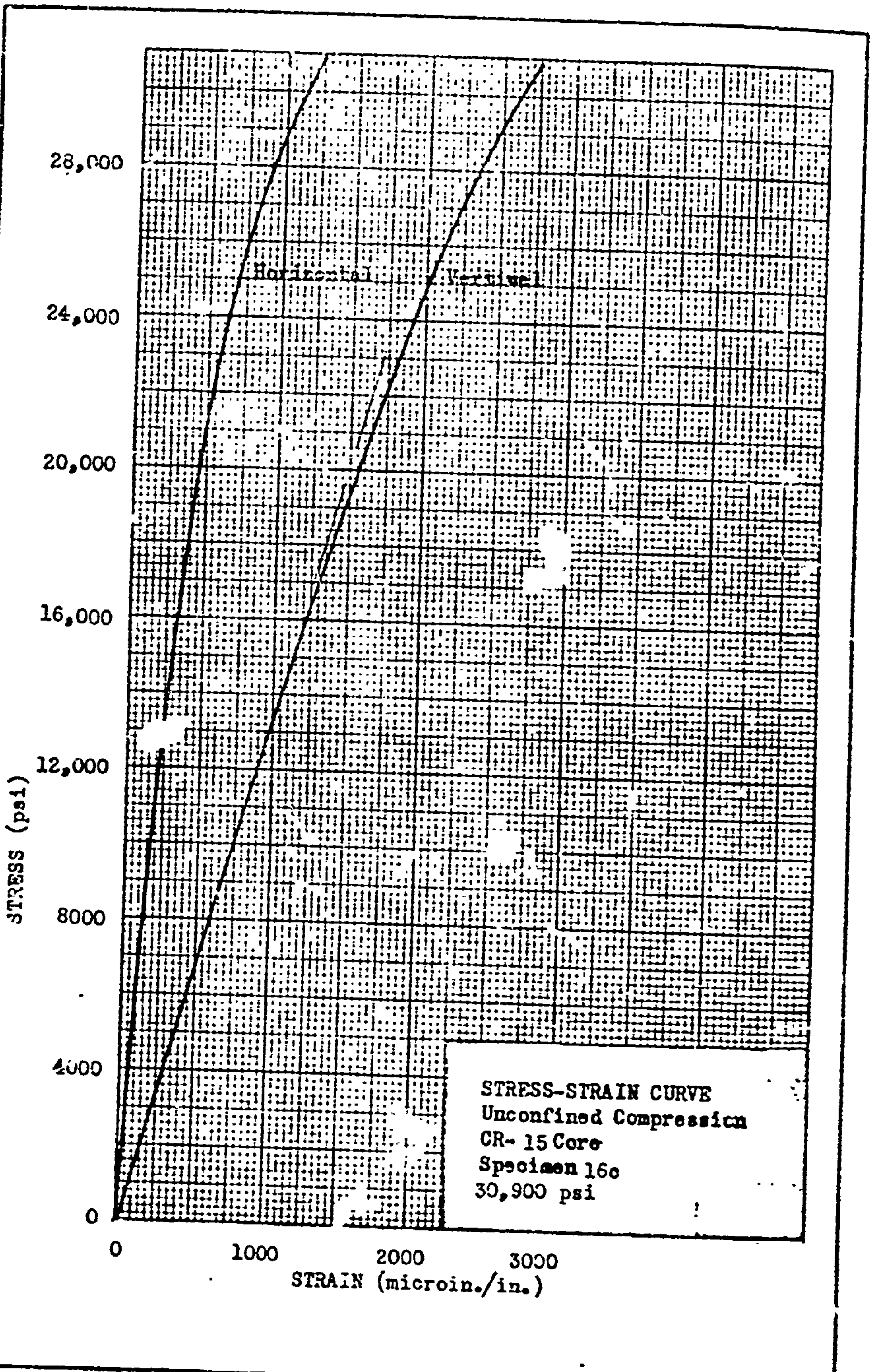

28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
Horizontal
Vertical
0
1000
2000
3000
STRAIN (microin./in.)
STRESS-STRAIN CURVE
Unconfined Compression
CR- 15 Core
Specimen 16c
30,900 psi

PLATE 9

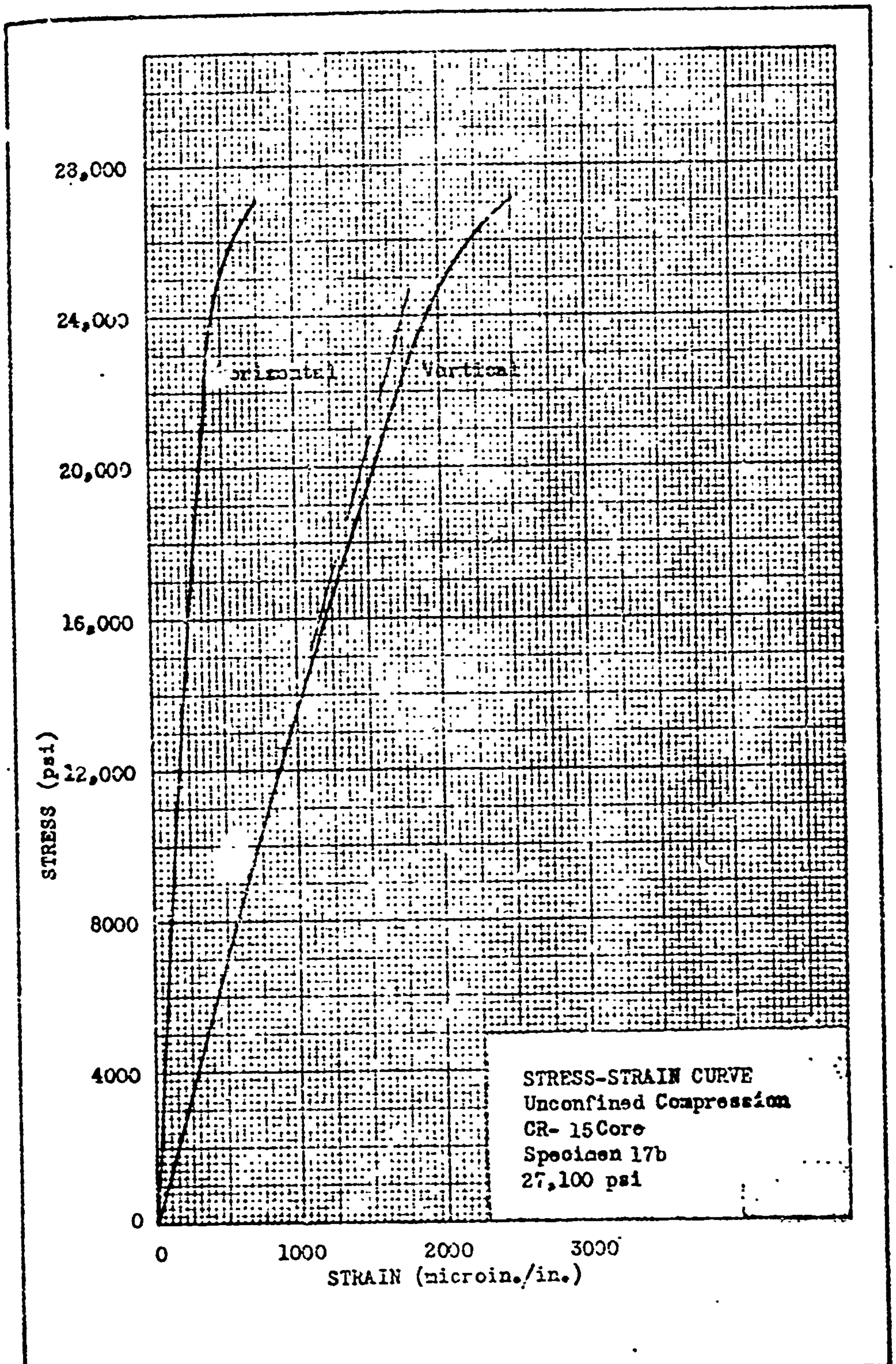

28,000
24,000
20,000
16,000
12,000
8000
4000
0
STRESS (psi)
0
1000
2000
3000
STRAIN (microin./in.)
Vertical
STRESS-STRAIN CURVE
Unconfined Compression
CR- 15 Core
Specimen 17b
27,100 psi

PLATE 10

Posttest Photograph

APPENDIX L

THERMAL PROPERTY TESTS

11 February 1959

U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION

AIR MAIL

CORPS OF ENGINEERS
OFFICE OF THE DIRECTOR
VICKSBURG, MISSISSIPPI 39181

REFER TO WESCC

11 February 1959

SUBJECT: Thermal Property Tests of Warren Area Cores

Commander
Space and Missile Systems Organization
ATTN: 1Lt R. G. Tart, Jr. (SMQHF)
Norton Air Force Base, California 92409

1. As requested by 1Lt R. G. Tart, Jr. of your office and Mr. M. V. Anthony of TRW, Inc., thermal property tests were conducted on samples of core from four holes in the Warren Siting Area: GR-4, 15, 19, and 35. The thermal diffusivity and specific heat were determined by test, and the thermal conductivity was calculated for each of the samples.

2. The cores were sawed to 6-in. lengths and drilled axially with small diamond drills. An iron-constantan thermocouple coated with waterproof cement was placed at the center of each core and grouted in place. The thermocouple was connected in series with a similar thermocouple placed in a cooling bath to form a differential thermocouple system which was connected to a potentiometer. The cores were placed in heating baths and brought to equilibrium. At the 120 F equilibrium temperature, readings were taken and the specimen suddenly immersed in a cooling bath of running water at about 50 F. Temperature readings accurate to 0.02 F were taken at various times during the cooling period. The times were noted to within a few thousandths of a minute. The time-temperature cooling curves were then graphed. The thermal diffusivities of the cores were computed from the time-temperature curves by use of the following formula:

$$T/T_o = C\left(\frac{h^2 t}{60R^2}\right) \times S\left(\frac{h^2 t}{60L^2}\right)$$

where:

T = temperature difference at time t, F

T_o = initial temperature difference, F

h^2 = diffusivity, ft^2/hr

R = radius of core, ft

(Continued)

WESCC 11 February 1959
SUBJECT: Thermal Property Tests of Warren Area Cores

(Continued)

t = time after immersion in cooling bath, min

L = length of specimen, ft

C(X) and S(X) are functions expressing a solution of the diffusion equation for a finite cylinder. Explanation of and values for these functions are given in Heat Conduction, Ingersoll, L. R., Zobel, O. I., and Ingersoll, A. C., pp 183-5, 256, 260, McGraw-Hill Book Co., 1948.

3. The specific heat was determined according to the test method CRD-C 124-62 (Incl 1). The thermal conductivity was computed from the relation for concrete given in method CRD-C 44-63 (Incl 2).

4. The results are given in table 1 (Incl 3). Apparently, the thermal properties of all the rock types examined are quite similar with the exception of the rock from hole CR-19 previously identified as soda diorite.

FOR THE DIRECTOR:

3 Incl (quad)
as

BRYANT MATHER
Engineer
Chief, Concrete Division

Copies w/incl furnished:
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J. Isenberg, AJA
S. Schuster, Applied Theory, Inc.
P. Pieper, TRW, Inc.
M. V. Anthony, TRW, Inc. (dupe)
P. Gallo, Ken O'Brien & Assoc.

CRD-C 124-62

METHOD OF TEST FOR SPECIFIC HEAT OF AGGREGATES (Method of Mixtures)

Scope

1. This method of test covers a procedure for determining the mean specific heat of aggregates by the method of mixtures using particles smaller than 1 in. in size.

Note.- When more precise values are desired and the specimen may be pulverized or ground to pass a No. 20 sieve the method given in CRD-C 242 should be used.

Apparatus

2. The apparatus used in this test shall consist of:

(a) Calorimeter.- A calorimeter of the vacuum-flask type with external insulation, large enough to accommodate samples of approximately 2 lb in weight placed in a wire basket, and provided with an insulated cover in which are openings for thermometer and stirrer.

(b) Thermometer.- A thermometer graduated to 0.1 F, in the range 32-150 F.

(c) Constant Temperature Bath, Hot.- An electrically heated constant temperature bath with thermostat set at approximately 125 ± 1 F.

(d) Constant Temperature Bath, Cold.- A refrigerated bath, with refrigeration thermostatically controlled at approximately 35 ± 1 F.

(e) Basket.- A wire-mesh basket, of material of known specific heat, approximately 4 in. in diameter by 4 in. high.

(f) Balance.- A balance capable of weighing 5 lb with an accuracy of ± 0.005 lb.

(g) Standard Specimen.- A specimen of material of known specific heat, with the product of mass times specific heat equal to approximately 0.4 B/lb.

(h) Timer.- A timer reading in minutes and seconds.

Specimen

3. For determinations of mean specific heat of aggregates according to the method outlined herein the specimen to be used shall consist of approximately 2 lb of the aggregate to be tested. The specimen shall contain no particles larger than 1 in. in size. When the material to be tested includes larger particles they shall be crushed before testing.

Note.- If a larger calorimeter is used the weight of the specimen may be increased proportionally.

Procedure

4. (a) Determination of the Water-Equivalent of the Calorimeter.- Approximately 2 lb of water, weighed to the nearest 0.01 lb shall be placed in the calorimeter. The calorimeter shall be placed in the constant temperature room until temperature equilibrium is attained. A weighed standard specimen of known specific heat shall be placed in the wire basket, the basket shall then be suspended by a fine wire in either the hot or the cold constant temperature bath until equilibrium is reached (about 15 minutes). The specimen shall have been weighed previously both dry, and in a dripping condition after immersion. The water carry-over shall be treated as described in Paragraph 5 below. The temperature of the constant temperature bath and of the water in the calorimeter shall be recorded to 0.05 F, and the standard sample shall be placed inside the calorimeter. The water in the calorimeter shall be stirred by manually raising and lowering the wire attached to the specimen. This supporting wire shall pass through a minute hole in the cover. Temperatures shall be recorded each minute during the temperature change, and for several minutes after the maximum change has occurred. The time-temperature curve shall then be plotted as indicated by the example

Incl (1 of 2 sheets)

2 METHOD OF TEST FOR SPECIFIC HEAT OF AGGREGATES (C 124-62)

given in Fig. 1 and the curve shall be extrapolated as described below to correct for the heat lost during the time the measurements were being taken. The line EGF shall be so drawn that the area BFG is equal to the area EGC. The approximate position of line EGF shall be determined by inspection. The line between points E and F gives the maximum temperature change which the specimen would have attained had there been no heat loss from the calorimeter. This temperature change shall be used in the calculations described in Paragraph 5 below.

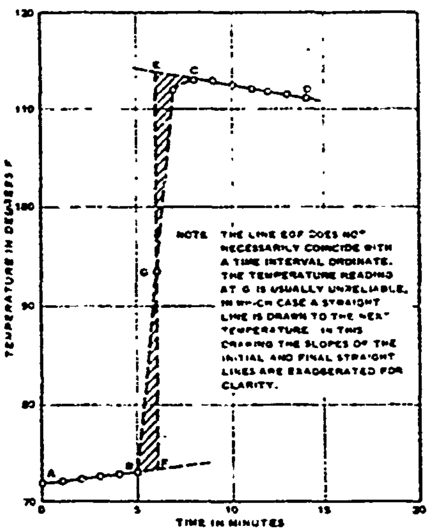

Fig. 1. Time-temperature history, specific heat determination

(b) Determination of the Mean Specific Heat of Aggregates.- The mean specific heat of an aggregate shall be determined by placing a weighed sample in either the hot or the cold water bath, and proceeding as in subparagraph 4(a). The sample shall have been weighed previously both dry, and in a dripping condition immediately after removal from the bath, and the water carry-over shall be treated in accordance with the calculations described in Paragraph 5 below. At least seven determinations shall be made. Hot and cold specimens shall be tested alternately in order to prevent the temperature of the water in the calorimeter from becoming greatly different from the room temperature, so that heat losses will be small or negligible.

Calculations

5. The water equivalent of the calorimeter and the mean specific heat of the sample of aggregate shall be calculated from the following formulas:

(a) Water Equivalent.-

$$M_e = \left[\frac{(c_s M_s T + c_1 M_o T + c_b m_b T)}{c_1 T_1}\right] - M_1$$

where:

M_e = water equivalent of calorimeter, lb,

c_s = mean specific heat of standard, B/lb-deg F,

M_1 = weight of water placed in calorimeter, lb,

c_1 = mean specific heat of water, B/lb-deg F,

Note.- The specific heat of water may be assumed to be 1.000 Btu/lb-deg F without significant error.

T_1 = temperature change of water, corrected for heat loss, deg F,

M_s = weight of sample, lb,

M_o = weight of water carry-over, lb,

T = temperature change of sample, corrected for heat loss, deg F,

c_b = specific heat of basket, B/lb-deg F, and

M_b = weight of basket, lb.

(b) Mean Specific Heat.-

$$c_s = \frac{(M_1 + M_e)c_1 T_1 - (M_o c_1 + M_b c_b)T}{M_s T}$$

where:

c_s = mean specific heat of specimen, B/lb-deg F, and

the remaining symbols have the same meaning as above.

Incl 1 (2 of 2 sheets)

(Issued 1 June 1963)

CRD-C 44-63

METHOD FOR CALCULATION OF THERMAL CONDUCTIVITY OF CONCRETE

Scope

1. This method is suitable for calculating the thermal conductivity of concrete from results of tests for diffusivity and specific heat.

Calculation

2. (a) The thermal conductivity of concrete shall be calculated from the following equation:

$$k = \alpha s W$$

where:
k = thermal conductivity, Btu/ft-hr-deg F,
α = thermal diffusivity, ft^2/hr,
s = specific heat, Btu/lb-deg F,
W = actual unit weight, lb/ft^3.

The thermal diffusivity of concrete shall be determined using either Method CRD-C 36 or CRD-C 37. The specific heat of the concrete shall be determined according to the procedure of Method CRD-C 124. The unit weight of concrete shall be determined using the procedures of Method CRD-C 7.

(b) The thermal conductivity of lightweight concrete and similar materials at various moisture contents shall be calculated from the following equation:[1]

$$k = \alpha C$$

where:
k = thermal conductivity, Btu/ft-hr-deg F,
α = thermal diffusivity, ft^2/hr,
C = volumetric heat capacity, Btu/ft^3-deg F.

The thermal diffusivity shall be determined using method of test for thermal diffusivity of lightweight concrete and similar materials. A curve shall be made of diffusivity versus moisture content for the range used. The volumetric heat capacity shall be calculated from the following equation:

$$C = \gamma\left(c_1 + \frac{w}{100}\right)$$

where:
C = volumetric heat capacity, Btu/ft^3-deg F,
γ = dry unit weight, lb/ft^3,
c_1 = specific heat of dry sample,
w = moisture content, percent dry weight.

The specific heat of material removed from diffusivity specimen shall be determined according to the procedure of Method CRD-C 242.

Report

3. The calculated value for thermal conductivity shall be reported to two decimal places, e.g., k = 1.35 Btu/ft hr-deg F.

[1] Procedure based on paper: "Tests for Thermal Diffusivity of Granular Materials" by William L. Shannon and Winthrop A. Wells, published in *Proceedings of the American Society for Testing Materials*, Vol 47, 1947.

Incl 2

TABLE 1

Thermal Properties of Warren Area Cores

Hole No.	Core No.	Depth, ft	Density, lb/ft^3	Diffusivity, ft^2/hr (1)	Specific Heat, BTU/lb-F (2)	Conductivity*	
						FPH	CGS x 10^3
CR-4	14	182	167.4	0.053	0.1936	1.72	7.104
CR-15	19	192	179.8	0.049	0.1878	1.65	6.814
CR-19	2	16	176.8	0.032	0.1893	1.07	4.419
CR-35	8	23	166.4	0.051	0.1897	1.61	6.649

* FPH = BTU/(hr)(ft^2)(deg F per ft);
CGS = cal/(sec)(cm^2)(deg C per cm).

NOTE: (1) Average of two tests.
(2) Average of seven tests.

Incl 3

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13. ABSTRACT

Laboratory tests were conducted on rock core samples received from ten core holes drilled in the Laramie range, Wyoming, to determine the integrity and mechanical behavior of the materials. The results were to be used to determine the usefulness of the Warren Siting Area for potential missile sites. Series I tests (relative hardness, specific gravity, compressive strength, sonic velocity, etc.) indicated the materials to be relatively uniform, competent granite, diorite, and gneiss rock. Series II tests (triaxial, hydrostatic, and confined compression) indicated the rock to be rather incompressible and brittle up to 36,000-psi triaxial stress. Series III tests indicated that the granite and diorite had Hugoniot elastic limits of 50 kilobars or more and the gneiss approximately 20 kilobars. In order to better define the physical and mechanical behavior of the rock, triaxial tests to approximately 150,000 psi on intact and jointed specimens and equation of state tests at pressures to approximately 600 kilobars should be conducted.

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Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rock cores						
Rock properties						
Rock tests						
Warren Siting Area, Wyo.						

Unclassified

Security Classification

END